SYNTHESIS AND PHOTOCHEMISTRY OF NEW CARBENE PRECURSORS

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation

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By

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ABSTRACT

Carbenes are neutral divalent reactive intermediates containing a carbon atom surrounded by only six valence electrons. Because of this electron deficiency, carbenes are very short-lived intermediates and react with a variety of functional groups. One of the most commonly used applications of carbenes is in cyclopropane synthesis.

This research has focused on the synthesis of new, novel carbene precursors and the study of their photochemistry. The purpose of this research is twofold: 1) to trap the carbene with pyridine and characterize the UV spectra of the carbene ylide intermediate and 2) to determine the lifetimes and reaction rates of carbenes with various reagents. The lifetime of the carbene and the rate of its reaction with alkenes will be used to form a better understanding of the relationship between carbene structure and reactivity.

Laser Flash Photolysis (LFP) techniques were used to generate the carbene, which subsequently reacted with pyridine to form an ylide. This reaction was necessary because we were not able to detect the carbene directly. The carbenes being studied cannot be directly detected because they do not exhibit a UV chromophore at or above 300 nm. Trapping the carbene with pyridine yields a species with a strong UV absorbtion at 480 nm, which is easily detected.

The lifetimes of bromo-substituted carbenes are much shorter than their fluoro-substituted or chloro-substituted analogs. Fluorine is able to stabilize the lone pair of electrons on the carbon much better than the bromine. Fluorine can also stabilize carbenes by donation of a lone pair of electrons into an empty orbital of the carbene. It has also been observed that as the other substituent on the carbene precursor becomes more electron-withdrawing, the carbon-bromine bond undergoes homolysis to form a bromine radical when irradiated with 308 nm light. To overcome this complication the bromine has been replaced with a hydrogen atom. A carbon-hydrogen bond does not undergo homolytic bond cleavage to form a hydrogen radical when irradiated with 308 nm light, and, therefore, the desired carbene can be formed and react with pyridine to form the intended ylide.

ACKNOWLEDGMENTS

I wish to thank Dr. Matthew Platz for giving me the great opportunity to do research over the past two years and his constant encouragement throughout that time.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SCHEMES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The search for new synthetic compounds and a means of optimizing synthetically useful reactions has constantly been the focus of synthetic chemists. Reaction rates, energy pathways, transition states, and reaction intermediates are aspects that must be understood in order to develop a comprehensive understanding of the reaction. Systematic investigation of carbenes, very reactive short-lived intermediates, began in the 1950's. Carbenes are neutral, divalent carbon compounds containing two singly covalently bonded substituents and two unshared electrons.[1] The reactivity of the carbene is derived from the electron deficiency of the carbon atom. The archetypal reaction of carbenes is the formation of cyclopropanes from alkenes. Because of the ability to place a number of different functional groups on the carbene, this is an effective method of synthesizing many novel substituted cyclopropane molecules. Carbenes are able to perform a variety of reactions other than addition to alkenes, which is due to the electrophilic and nucleophilic, p-orbital and sp^2-orbital respectively, character of the molecule. This allows the carbene to be attacked by a nucleophilic molecule, in the case of ylide formation **(1)**, and in the case of alkene addition **(2)** (Figure 1.1).

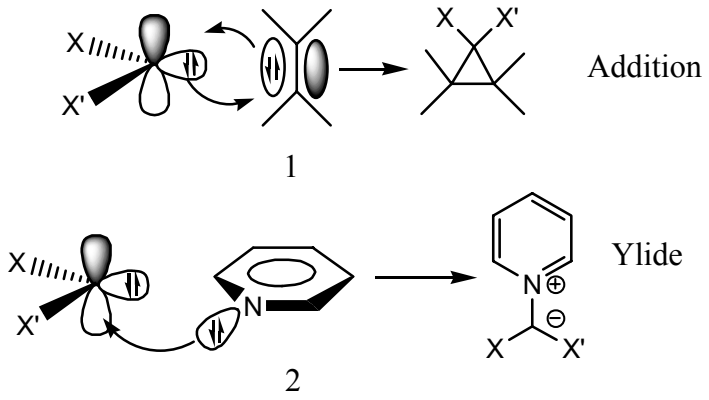


Figure 1.1. Reactions of carbenes.

A carbene can exist either in the singlet state **(3)**, in which both unshared electrons have opposite spins, or a triplet state **(4)**, with both unshared electrons having the same spin, and, therefore, must be in different orbitals.

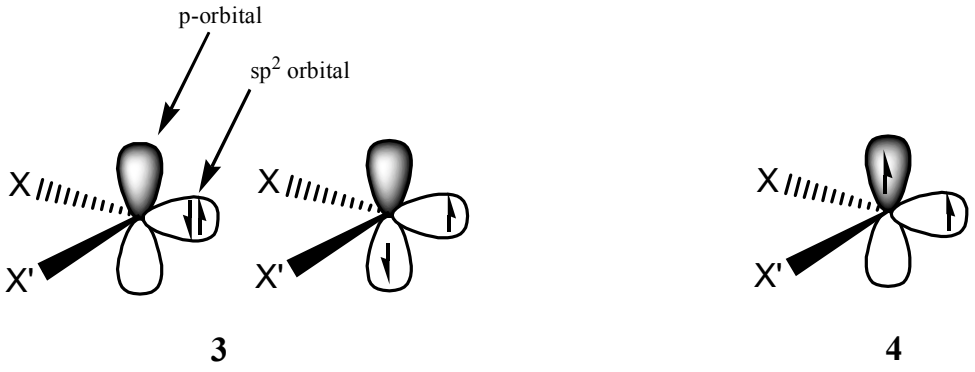


Figure 1.2. Singlet and triplet states of a carbene.

Hine was one of the first modern chemists to hypothesize the formation of a carbene in 1949.[2] He found that chloroform was much more reactive toward basic hydrolysis than carbon tetrachloride or methylene chloride.[2] Hine rationalized that the three chlorine atoms of chloroform were sufficiently electron-withdrawing that the removal of the hydrogen atom was easily accomplished with a basic molecule. The chlorine atoms stabilized the resulting anion, but formation of the carbene is favorable and a chloride ion is lost.

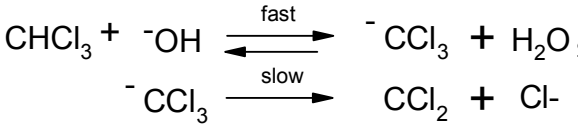


Figure 1.3. Formation of dichlorocarbene from chloroform.

Hine's theory was supported by the work of Doering and Hoffman who demonstrated that dichlorocarbene would add to an alkene under Hine's reaction conditions.[3] They found that chloroform reacted very well with alkenes, forming dichloro-substituted cyclopropane groups.

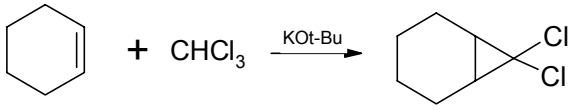
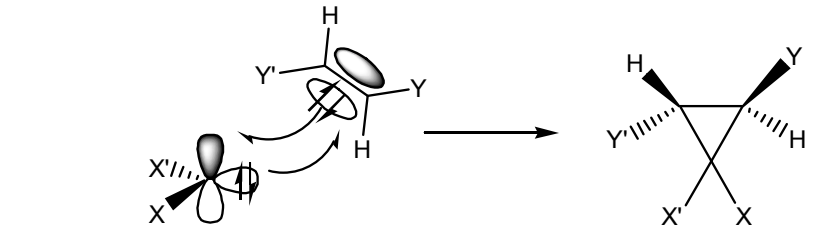
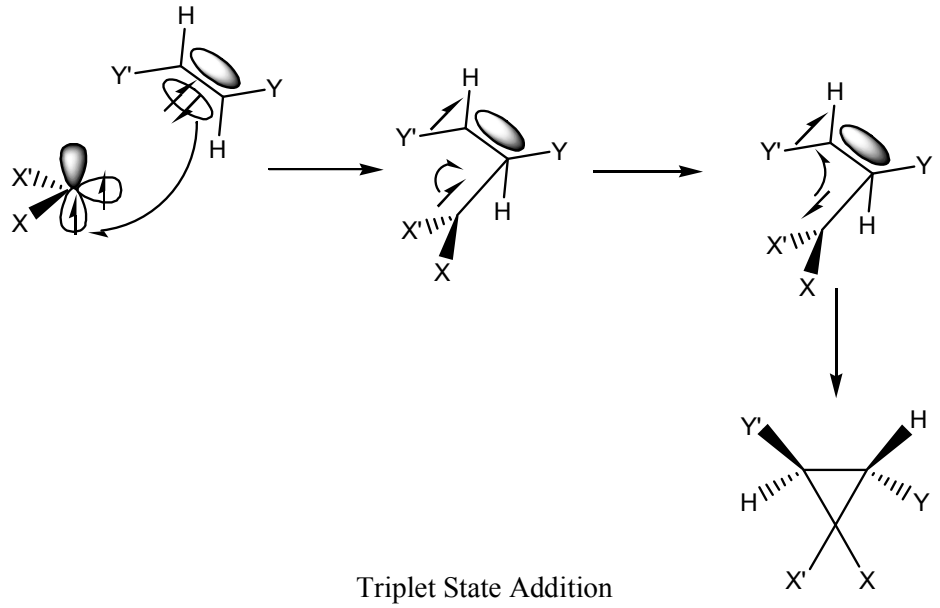


Figure 1.4. Addition of a carbene to an alkene.

This reaction was found to be stereospecific by Skell and Garner; the stereochemistry present in the alkene was preserved in the formation of the three-membered ring.[5] A mechanism was proposed that involved a concerted addition of the carbene to the double bond of the alkene.[5] In order for the mechanism to be spin allowed the carbene must be a singlet state species because the triplet state must react in two steps.



Singlet State Addition



Triplet State Addition

Figure 1.5. Singlet and Triplet State additions to alkenes.

The first step in the triplet state addition is the formation of a biradical as one carbon-carbon bond is created. The triplet biradical must undergo an intersystem crossing before it can bond with the other carbon radical. Since carbon-carbon bond rotation occurs at a faster rate than intersystem crossing, the most thermodynamically stable product would be formed regardless of the configuration of the starting material.[6] Carbene addition will be stereospecific unless the triplet state is readily accessible.[7]

The lifetimes of carbenes can be effected by the stability of the carbenic center. A heteroatom that donates electron density to the empty p-orbital of the carbenic center will stabilize the carbene, while an electron withdrawing heteroatom will destabilize the carbene and decrease its lifetime. Halogen substituents have been shown to have an

effect on the lifetimes of the carbene by its stabilizing effects. Dichlorocarbene has a lifetime in solution between 100 and 200 ns while chlorocarbene has a lifetime of only a few nanoseconds.[8,9]

In the 1960's flash photolysis became a useful method to study carbenes. In 1980 the laser flash photolysis (LFP) technique became widely used.[10] Since many carbenes do not contain a useful UV chromophore, they cannot be detected directly in an LFP experiment. Pyridine ylides, formed by the reaction with the carbene, are UV active and can be used to indirectly detect the presence of and determine the rate constants of reaction of the carbene. A plot of k_{obs} versus pyridine concentration has a slope of k_{pyr} and an intercept of k_0.[4] The carbene lifetime can be defined as $1/k_0$. The yield of the ylide will no longer be increased above a certain pyridine concentration. By adding competitive carbene traps (alkenes), k_{obs} will increase and decrease the yield of the pyridine ylide. The rate constant of addition for the carbene to the alkene can be calculated by varying the concentration of the alkene. This will allow for a better understanding of the reactivity and stability of the carbene.

CHAPTER 2

BROMO-SUBSTITUTED CARBENES

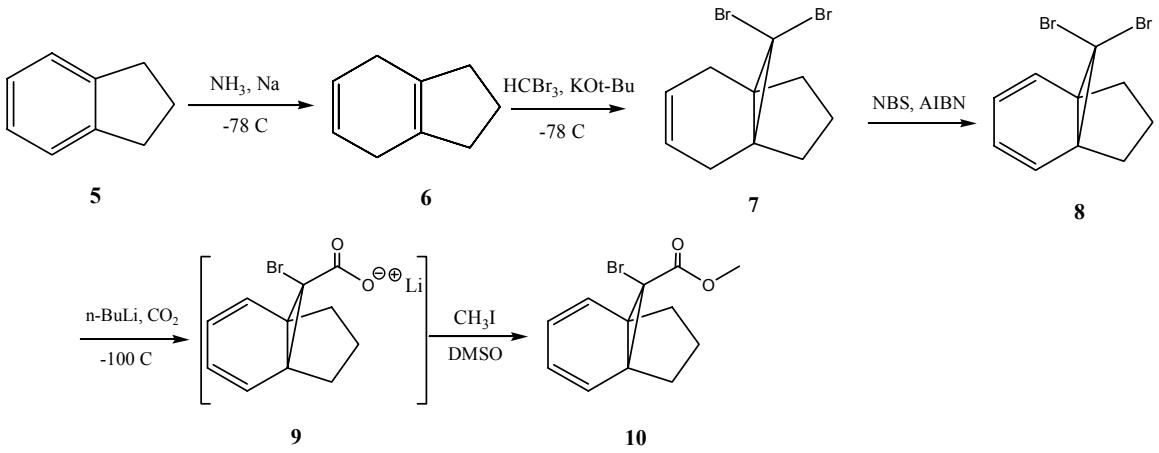
2.1 Synthesis of Carbene Precursors

2.1.1 Bromocarbomethoxycarbene

A substituent on a carbene carbon can have a large effect on its kinetic behavior and lifetime.[11] It can increase or decrease the lifetime of the carbene by its ability to stabilize or destabilize the carbene. Halogens are able to influence carbene stability through resonance and inductive effects. The halogen atom can donate a lone pair of electrons to the empty p-orbital of the carbene through resonance. This allows the carbon atom to regain its octet of valence electrons, which, in turn, stabilizes the carbene. The species is still very reactive because of the unpaired electrons in the sp^2-orbital of the carbon atom, but the lifetime is prolonged. Since halogens are electron-withdrawing atoms, the electron density of the carbene center can be inductively withdrawn; also stabilizing the carbene.

The other substituent of the carbene can also have a large effect on the kinetic behavior and lifetime of the intermediate. Similar to the effects of the halogen substituent, the nature of the functional group that is present will influence the stability of the carbene. By studying the bromo-substituted carbenes it can be determined how well a certain functional group will stabilize the carbene.

The indan-based precursors were found to work well with bromo-substituted carbenes because fragmentation of the tricyclic precursor to regain aromaticity is very favorable.[9] This allows the carbene to be easily formed when the precursor irradiated with an intense light pulse. The synthetic route used to synthesize the bromocarbomethoxycarbene precursor is illustrated in Scheme 2.1.

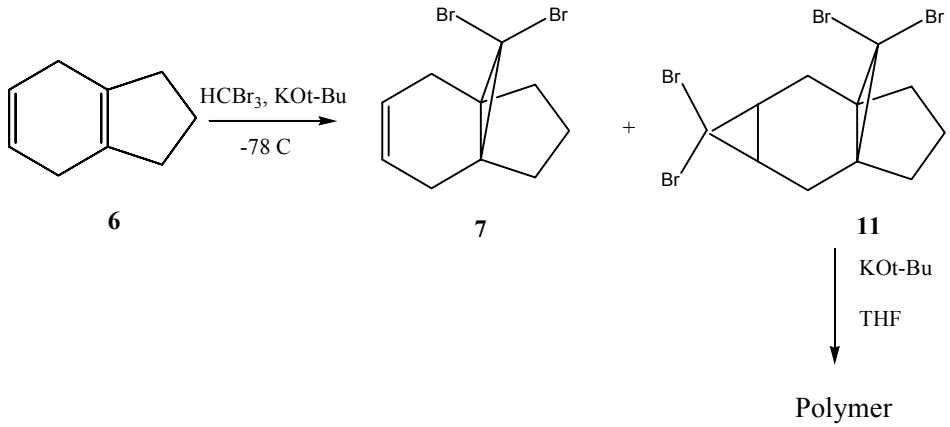


Scheme 2.1. Synthesis of 10-endo-bromo-10-exo-carbomethoxytricyclo[4,3,1,0]-deca-2,4-diene (**10)**.

The first step in this synthesis is to produce dihydroindan from indan by a Birch Reduction. This allows for the addition of the dibromocarbene across the double bond, which cannot be accomplished from indan due to the stability of the aromatic ring. In this reaction, the mixture needs to be stirred well in order to prohibit the sodium metal from clumping at the bottom of the flask. Dihydroindan and indan are not easily separated during the workup of the reaction and, therefore, it is important to make sure that 90% of the desired product is present at the completion of the reaction. H^1 NMR spectroscopy can be used to determine the ratio of product to starting material by comparing the intensity of the carbon-carbon double bond peaks of dihydroindan (~6 ppm) to the intensity of the aromatic peaks of indan (~7.3 ppm). If too much of the starting material remains at the end of the workup, the reaction should be repeated.

The addition of dibromocarbene across the internal double bond is easily preformed and well documented.[12] Preferably, the dibromocarbene adds across the more substituted double bond, but there is a tetra-brominated compound by-product that is formed when two dibromocarbene molecules add across both of the double bonds (Scheme 2.2). In order to reduce the amount of tetra-brominated compound formed, the reaction was preformed at low temperature and one equivalent of bromoform was added drop-wise over four hours. A small amount of byproduct was still formed (10-20%). Because the R_f values of the two compounds are very similar, 0.64 for the desired

product and 0.59 for the byproduct, they are not easily separated by column chromatography. A method was devised that consumed the tetra-brominated compound while leaving the desired product. In the presence of potassium *tert*-butoxide, the tetra-brominated compound forms a water soluble polymer. This reaction was not successful in hexane, but did work in THF. After the polymer was formed, the reaction mixture was washed with water and the di-brominated compound was extracted with hexane.



Scheme 2.2. Synthesis of 10,10-dibromo-tricyclo[4,3,1,0]deca-3-ene (**7**).

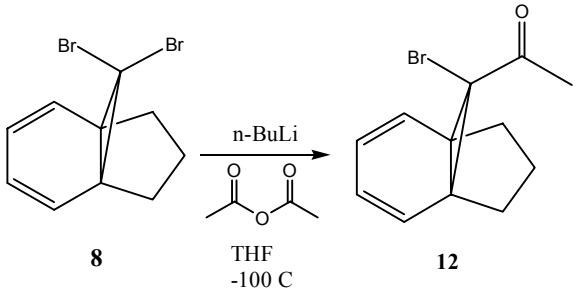
The procedure for the synthesis of the conjugated diene was developed by Condon.[13] This procedure produced a large amount of blue byproduct (probably an azulene) that was not easily separated from the desired product. The identity of this byproduct could not be determined, but when the reaction was run in cyclohexane instead of benzene, the amount of by-product greatly decreased. The less polar solvent, cyclohexane, also reduced the reaction time to 3 hours from more than 24 hours.

The synthesis of the ester was a two step process and involved the formation of a very stable salt intermediate. The addition of *n*-BuLi selectively removes the exo-bromine instead of the endo-bromine. The endo-bromine is bound strongly to the bridgehead carbon, which may be influenced by its position above the conjugated double bonds. A much more reactive reagent such as *tert*-BuLi or Et_2Zn must be used in order to remove the endo-bromine. Synthesis of the salt intermediate was accomplished by adding solid carbon dioxide to the reaction mixture of the dibromo diene and *n*-BuLi. It was extremely difficult to dissolve the salt in solution. Since water could not be used due

to the creation of the carboxylic acid, dioxane was the best solvent used to dissolve the salt. The salt did not completely dissolve in dioxane, but as the molecules in solution reacted with iodomethane, more of the solid dissolved and allowed the reaction to proceed. The formation of the salt became increasingly difficult as the anhydrous quality of the solid carbon dioxide decreased. A method was attempted that would attempt to dry the carbon dioxide gas with P_2O_5 and then bubble the gas through the reaction mixture, but this failed to yield the desired product. The continuation of the reaction sequence was halted due to the inability to reproduce this reaction and the removal of the endo-bromine could not be preformed.

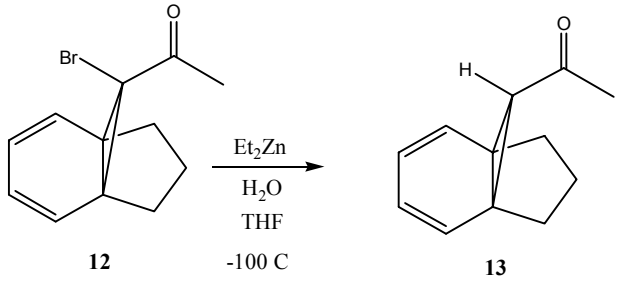
2.1.2 Acetyl-Substituted Carbene

In order to determine the effect of the exo-functional group on the behavior of the carbene, the acetylbromocarbene precursor was synthesized. This reaction was very straight- forward and similar to the synthesis of the bromocarbomethoxycarbene precursor. Acetic anhydride was used and was distilled along with the THF in order to prevent a reaction with water. A yellow, unidentifiable, liquid byproduct was formed in this reaction, and could only be removed by column chromatography. A large column was used for this because the R_f values or both the desired product and the byproduct were nearly identical. A structure of the yellow byproduct could not be determined from spectral analysis because of the complexity and amount of noise in the spectra. The acetic acid that was not neutralized in the workup of the reaction did not come off the column. The reaction yielded 50% of the bromocarbomethoxycarbene precursor.



Scheme 2.3. Synthesis of
10-endo-bromo-10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene (**12**).

The last step of the synthesis consisted of the reduction of the endo-bromine and proved to be difficult due to the reagent used. Diethyl zinc was needed to remove this bromine because of its stability and strength of the bond to the carbon atom. Et_2Zn oxidizes very rapidly in the presence of air in an extremely exothermic reaction. Problems were encountered in the transfer of the reagent into the reaction flask. An oven dried syringe and flushing the system with argon were not sufficient to prevent the air oxidation because a small amount of Et_2Zn that may have been present in the needle would react. A method was developed that would cantilever the reagent from the reagent bottle directly into the reaction flask utilizing argon pressure. Again this proved to be dangerous because the argon gas stream was not completely deoxygenated and the oxidation reaction would occur in the flask. The precise amount of Et_2Zn added to the reaction mixture became difficult to measure as smoke was produced in the flask from the reagent and counting the drops added from the cantilever was the only method to determine the amount added. Eventually this process was discarded and a new scheme was created that would use 1.0M Et_2Zn in THF. This was a much safer reagent and the use of a syringe was acceptable. Smoke was still produced in the reaction flask, but adding the reagent directly into the solution solved the problem. The synthesis yielded 40 % of the acetylcarbene precursor. This low yield may be derived from the need to warm the reaction mixture in order to add the water.

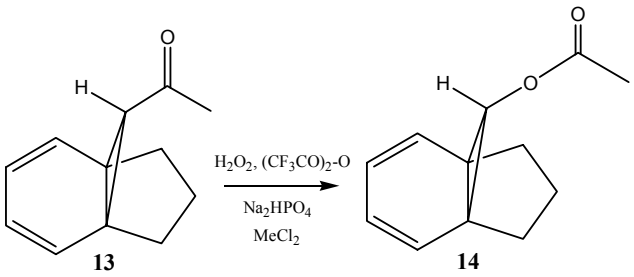


12 13

Scheme 2.4. Synthesis of 10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene.

A Bayer-Villager oxidation was preformed on 10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene in order to form the acetatecarbene precursor. This reaction was relatively

easy compared to the previously stated reaction. Three equivalents of trifluoroacetic anhydride are required to remove the water from the 50 % H_2O_2 and thorough mixing is required. Once the reagents were mixed, TLC was used to check the progress of the reaction. Because this synthesis is in its preliminary stages a full characterization of the molecule formed is not available. The difference in R_f values for the molecules (0.60 for the starting material and 0.42 for the product) was expected. This shows promise of being the desired molecule.

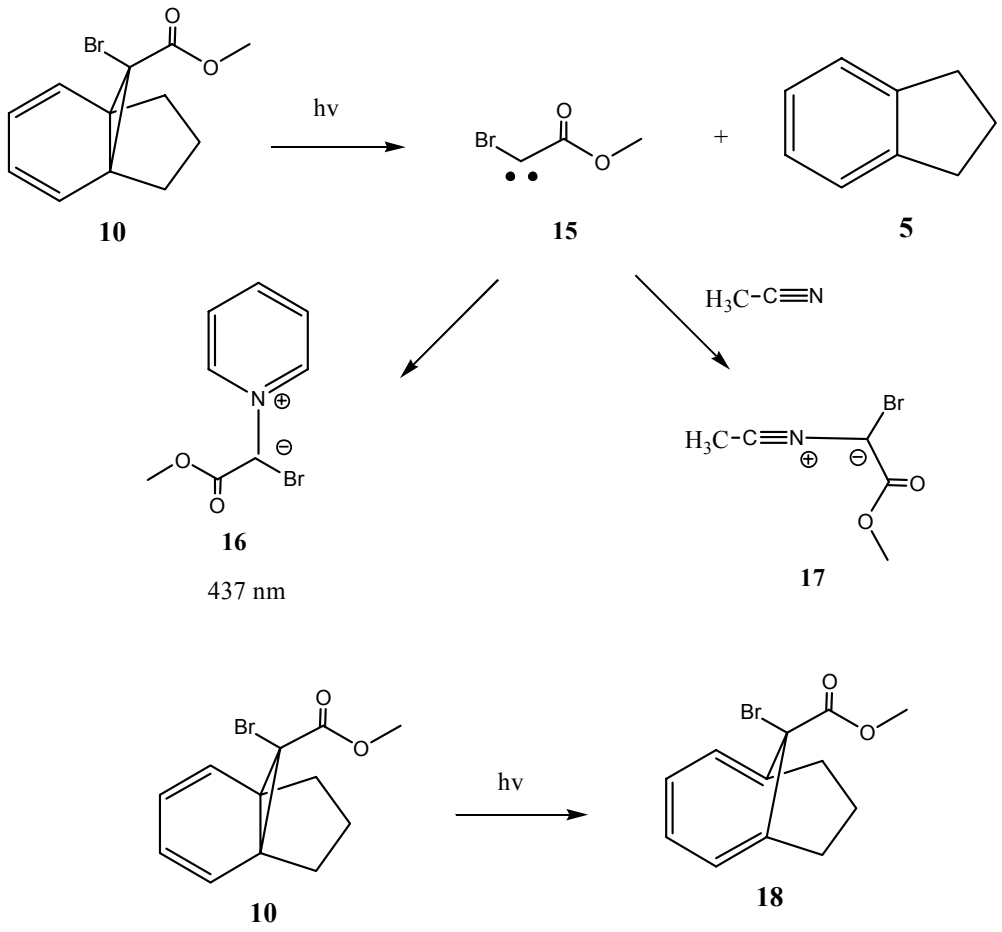


Scheme 2.5. Synthesis of 10-exo-acetatetricyclo[4,3,1,0]-deca-2,4-diene (**14**).

2.2 Laser Flash Photolysis Studies

2.2.1 Bromocarbomethoxycarbene

Laser flash photolysis (LFP) studies were performed at 308 nm with precursor (**10**) to study the bromocarbomethoxycarbene (**15**) in Freon-113, benzene, and acetonitrile (ACN). In each solvent 10 mmol pyridine was present in order to form the corresponding ylide. Ylide trapping is necessary because the carbene does not have a useful UV chromophore. In a few of the spectra, a transient peak, corresponding to the pyridine ylide (**16**), was not observed at 440 nm (Figures 2.1-2.3), demonstrating that the choice of solvent plays a large role in the formation and lifetime of the carbene. The absorbance near 325 nm is due to formation of a triene (**18**) due to the breaking of the carbon-carbon cyclopropane bond in the precursor.



Scheme 2.6. Reactions of bromocarbomethoxycarbene (**15**)

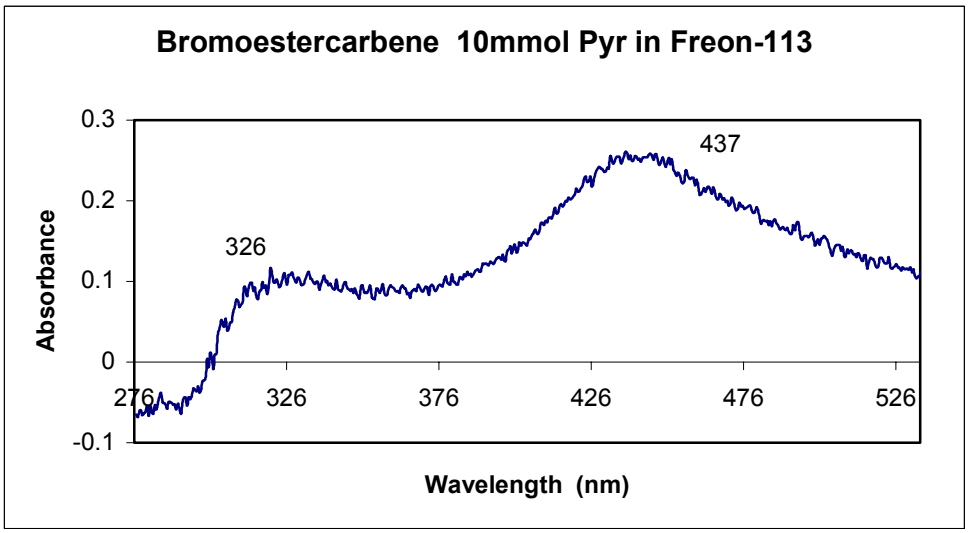


Figure 2.1. Transient absorption spectra produced by LFP of **15** in Freon-113 (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window.

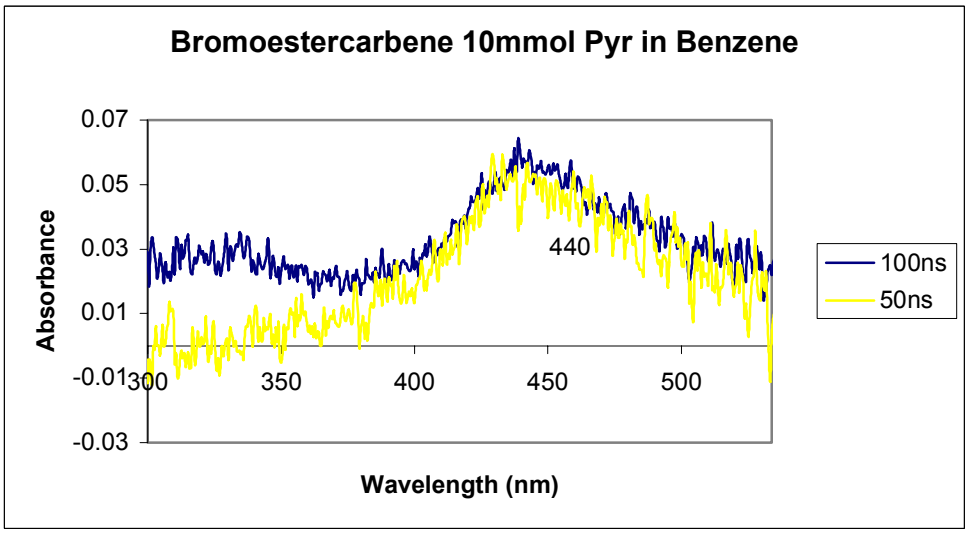


Figure 2.2. Transient absorption spectra produced by LFP of **15** in benzene (deoxygenated) at ambient temperature. The spectrum was recorded at 100 ns and 50 ns after the 308 nm laser flash over a 20 ns window.

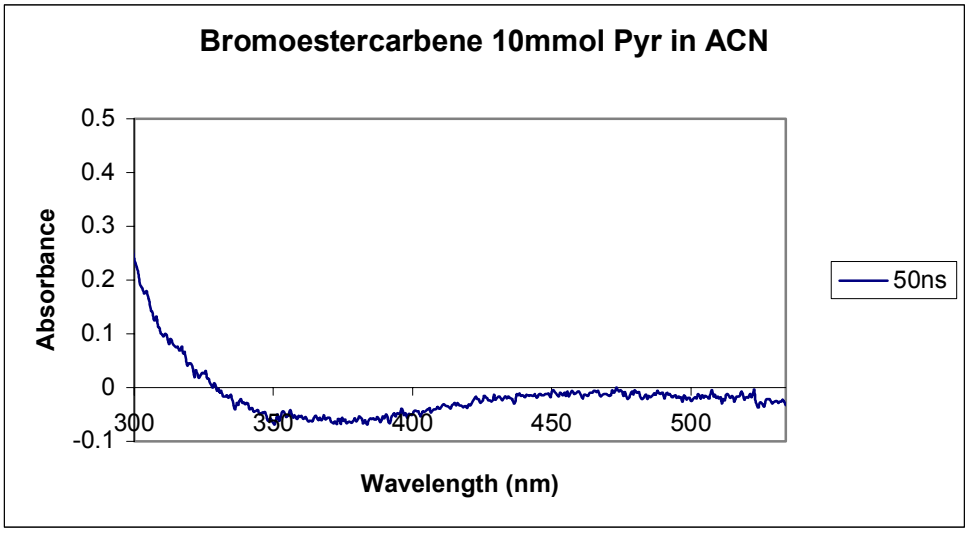


Figure 2.3. Transient absorption spectra produced by LFP of **15** in acetonitrile (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window.

In Freon-113, ylide **16** has an intense transient absorbance and it shows the most intense ylide signal of the three chosen solvents utilized. In benzene, an absorbance was seen at 440 nm, indicating that ylide **16** had formed, but the weak intensity of the signal indicates that there was a competing reaction present. Bonasso and Platz reported that bromocarbene reacted rapidly with benzene, showing a major peak at 315 nm.[4] This peak has shifted to 325 nm which is probably caused by the extra conjugation from the carbonyl functional group. Although the desired ylide can be seen in the spectrum, the reaction with benzene plays a major role in decreasing this intensity and further kinetic studies in benzene could not be continued. A similar problem was seen with ACN. The carbene likely reacted with ACN to form **17** instead of ylide **16**.

Kinetic studies were preformed to determine the lifetime of bromocarbomethoxycarbene. The formation of ylide **16** is too fast for direct measurement thus the optical yield (A_y) as a function of pyridine concentration was measured.[13] As the pyridine concentration increases, the yield of the ylide increases until the saturation point is reached; all of the carbene produced is trapped by pyridine. A double reciprocal plot will yield a straight line whose slope is equal to $k_{pyr} * \tau$, where k_{pyr} is the rate of trapping by pyridine and τ is the lifetime of the carbene.[9] The value for k_{pyr} was estimated to be $2*10^9$ M^{-1} s^{-1} as this was the rate constant for the chloroestercarbene determined by Tippman, Holinga, and Platz.[14] By using this rate constant, the lifetime of bromocarbomethoxycarbene was deduced to be 18 ns in benzene and 10 ns in cyclohexane. The difference in lifetime can be attributed to the ability of the solvent to stabilize the carbene. Benzene, the more polar solvent, is able to stabilize the carbene to a larger extent than cyclohexane.

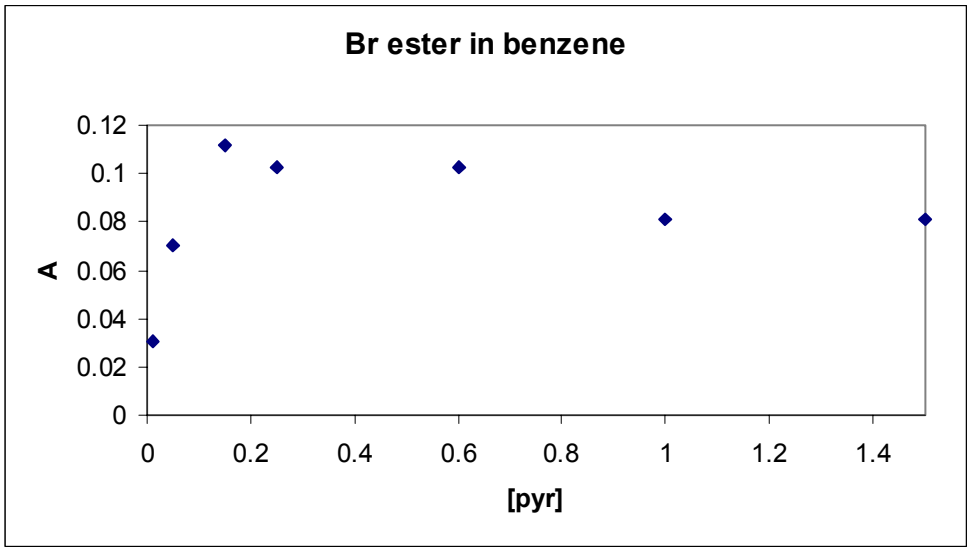


Figure 2.4. Optical yield of ylide **16** (A_y versus pyridine concentration).

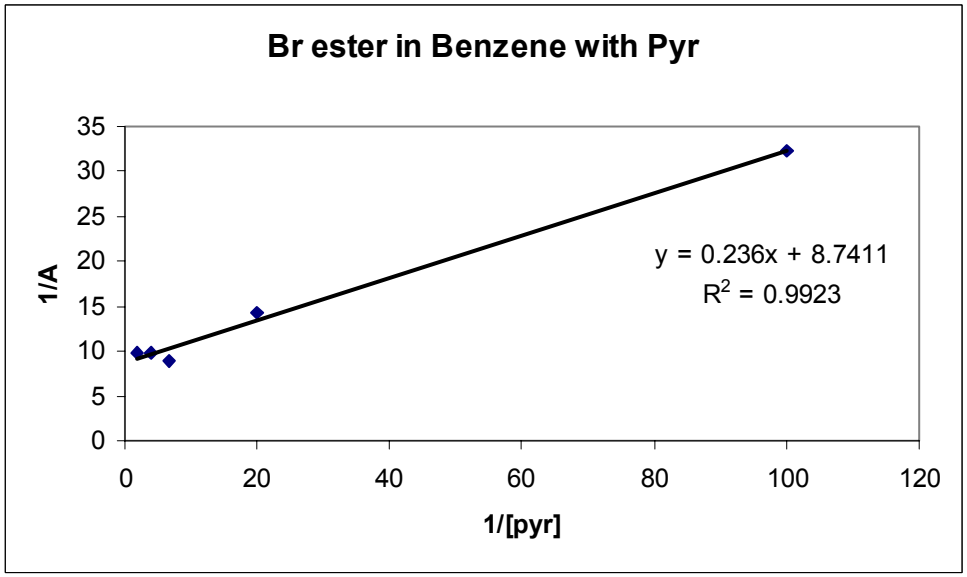


Figure 2.5. Double reciprocal treatment of the data of in Figure 2.4.

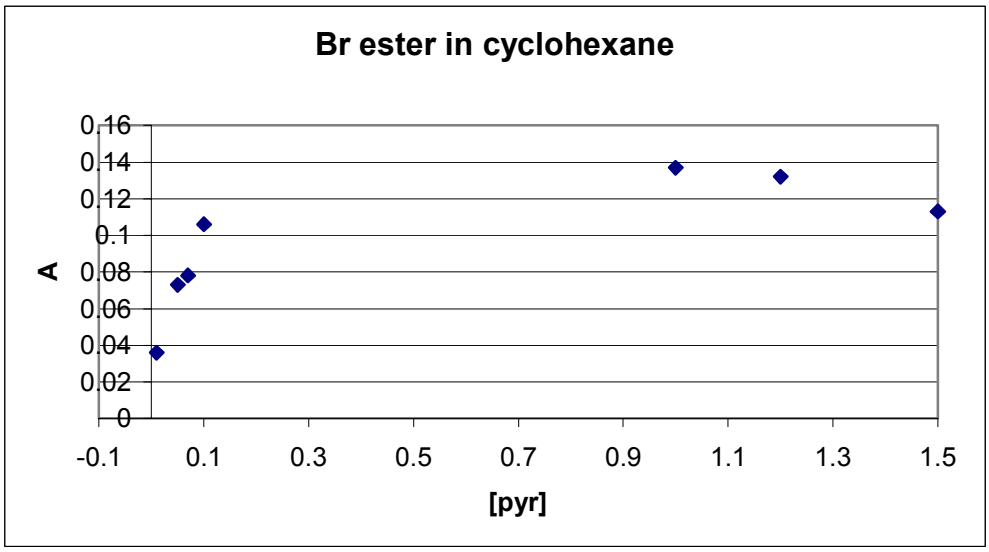


Figure 2.6. Optical yield of ylide **16** in cyclohexane.

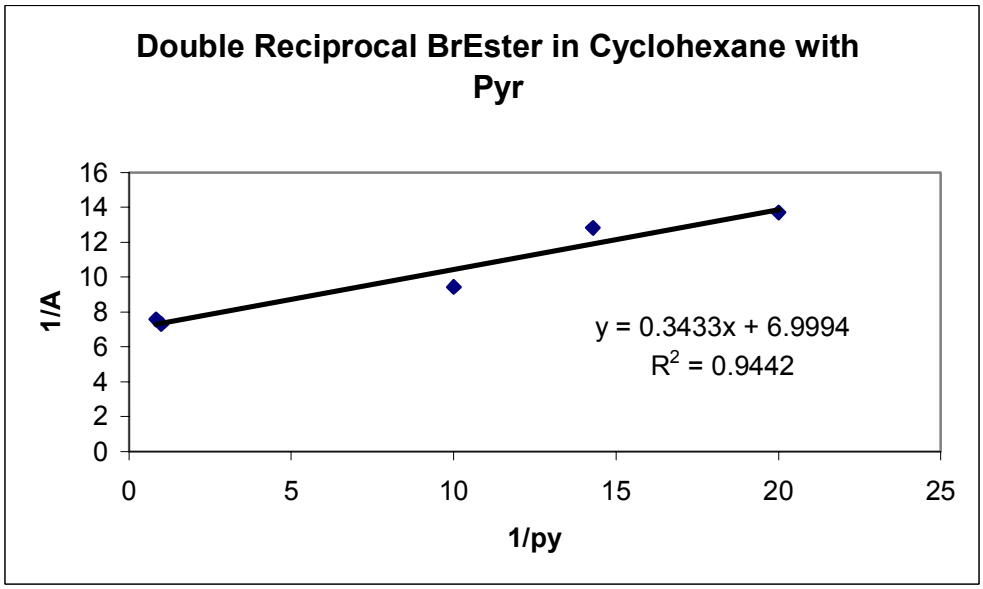


Figure 2.7. Double reciprocal treatment of the data of in Figure 2.6.

2.2.2. Discussion

The lifetime determined for bromocarbomethoxycarbene does not follow the trend established by Tippman, Holinga, and Platz. They determined the that the carbomethoxyfluorocarbene had a lifetime of 53 ns and the carbomethoxychlorocarbene had a lifetime of 114 ns under similar conditions.[14] By following this trend, the lifetime of the bromocarbomethoxycarbene should be about 200 ns, but it was deduced to be only 10 ns in cyclohexane and 18 ns in benzene.

	k_{pyr} ($M^{-1}s^{-1}$)	Lifetime τ (ns)
carbomethoxyfluorocarbene	6.7×10^9	53
carbomethoxychlorocarbene	2.0×10^9	114

Table 2.1. Comparison of halocarbene ester lifetimes.

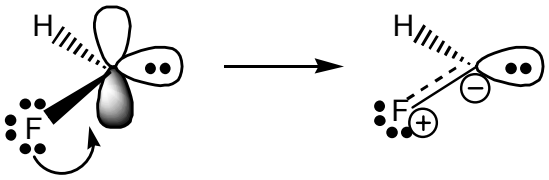
However, the lifetime of the carbene does follow the trend ascertained by Bonasso in which the lifetime of the carbene increases as the electronegativity of the heteroatom increases.[4] Bromocarbomethoxycarbene does indeed have the shortest lifetime of the three halocarbene esters, which is consistent with Bonasso's work.

	k_{pyr} ($M^{-1}s^{-1}$)	Lifetime τ (ns)
FCH	$8 \times 10^9 - 1 \times 10^{10}$	7-9
ClCH	8×10^9	2
BrCH	$5 \times 10^9 - 1 \times 10^{10}$	1-2

Table 2.2. Comparison of halocarbene lifetimes.

Comparing the three heteroatoms, fluorine shows the greatest stabilization of the carbene. This is due to the fluroine atom's ability to donate a pair of the electrons to the empty p-orbital of the carbenic center. The donation allows for the formation of a carbon-fluorine double bond. The fluorine becomes positively charged because it has

donated a pair of electrons, and pulls the lone pair of electrons in the filled carbenic orbital towards it. This action stabilizes the carbene and lengthens the lifetime. Bromocarbene does not demonstrate this stabilization because of its size and electronegativity. Bromine cannot effectively donate a pair of electrons to the empty p-orbital of carbon because of the mismatch of the size of the orbitals on bromine and carbon, and, therefore, does not easily form the double bond that will stabilize the carbene.



Scheme 2.7. Stabilization of fluorocarbene.

When comparing the halocarbene esters to the halocarbenes, it is observed that the addition of an ester group significantly increases the lifetime of the carbene.

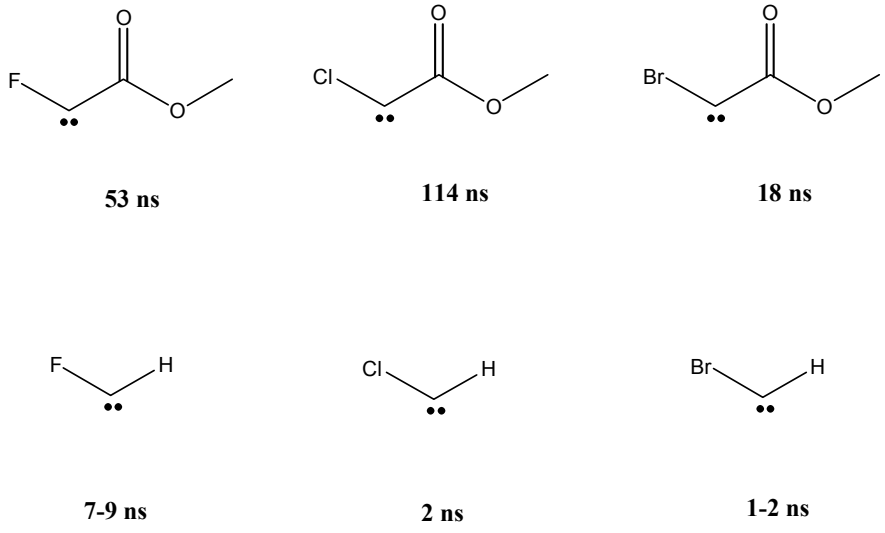


Figure 2.8. Comparison of lifetimes of halocarbene esters to halocarbenes.

The π-system of the carbonyl interacts with the filled orbital of the carbenic center and, in effect, delocalizes the electron density about the three atoms. This allows the electron deficient carbon to gain electron density, which will stabilize the carbene. In order for the π-system and the filled p-orbital to interact, the orbitals of the carbonyl and carbenic carbon need to be parallel to one another. Optimal orbital overlap can be achieved in this configuration and electron density can be optimally delocalized. The halogen will be perpendicular to the carbonyl group in this arrangement.

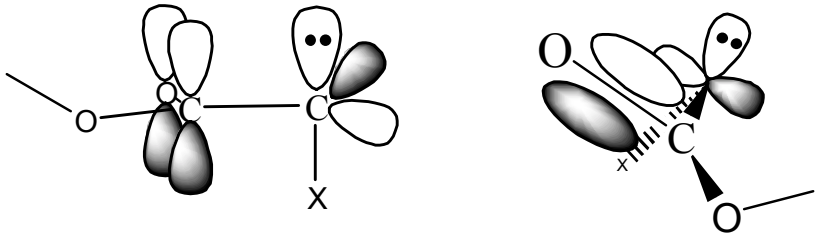
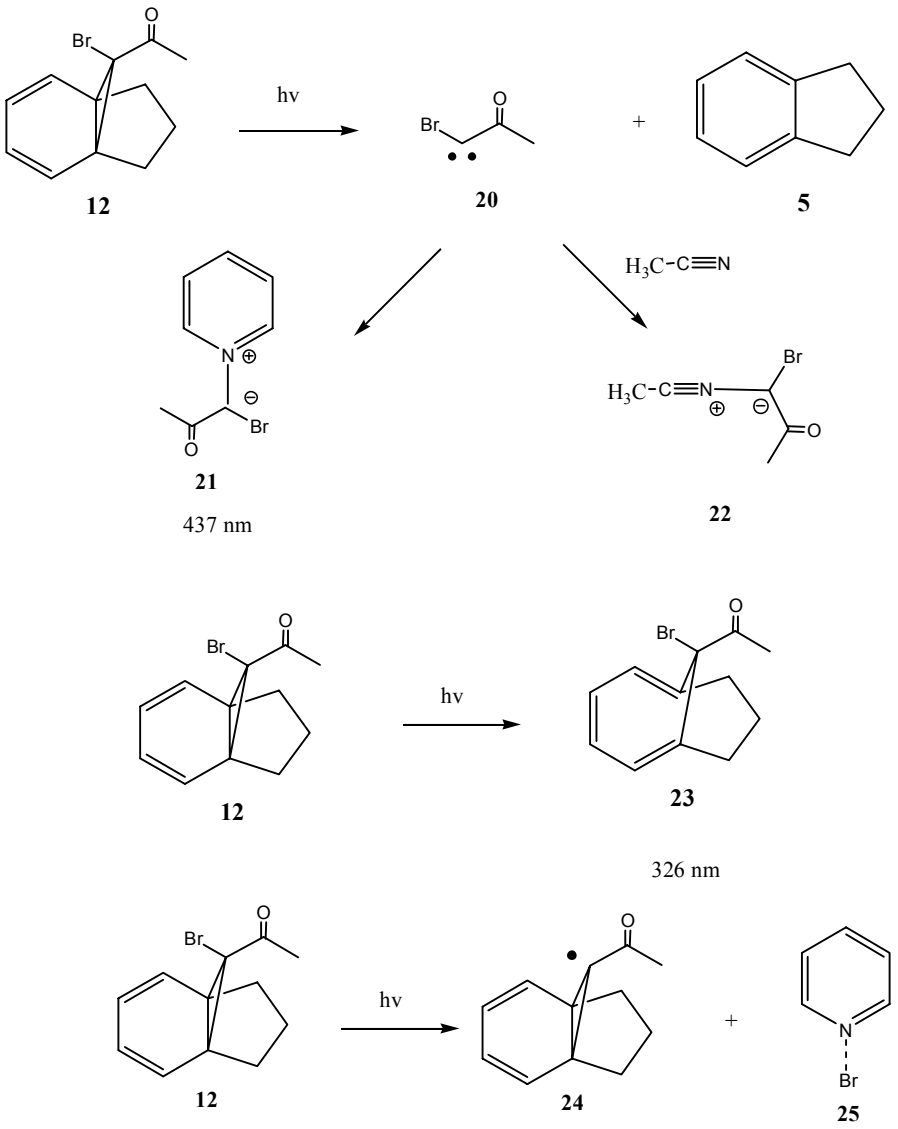


Figure 2.9. Orbital configuration of halocarbene ester.

2.2.3 Acetylbromocarbene

LFP studies were preformed at 308 nm with precursor **12** to study acetylbromocarbene in dichloromethane, THF, and ACN. In each solvent, 10 mmol pyridine was present in order to form the corresponding ylide because the carbene does not have a useful UV chromophore. In the resulting spectra the transient corresponding to the ylide was observed at 440 nm (Figure 2.8 – 2.10). This transient peak did not show a strong absorbance in any of the solvents, indicating that there must be a competing reaction. These reactions may be the formation of the triene, as shown to form in the photolysis of the bromocarbomethoxycarbene precursor, or the formation of a ketone radical. The complex of bromine with pyridine and the triene both show absorptions near 320 nm. Less of the desired carbene is formed due to these competing reactions and, therefore, the intensity of ylide **21** is fairly weak.

Due to the weak absorbance of the ylide, further kinetic studies to determine k_{pyr} and the lifetime (τ) of the carbene could not be preformed.



Scheme 2.8. Reactions of Acetylbromocarbene.

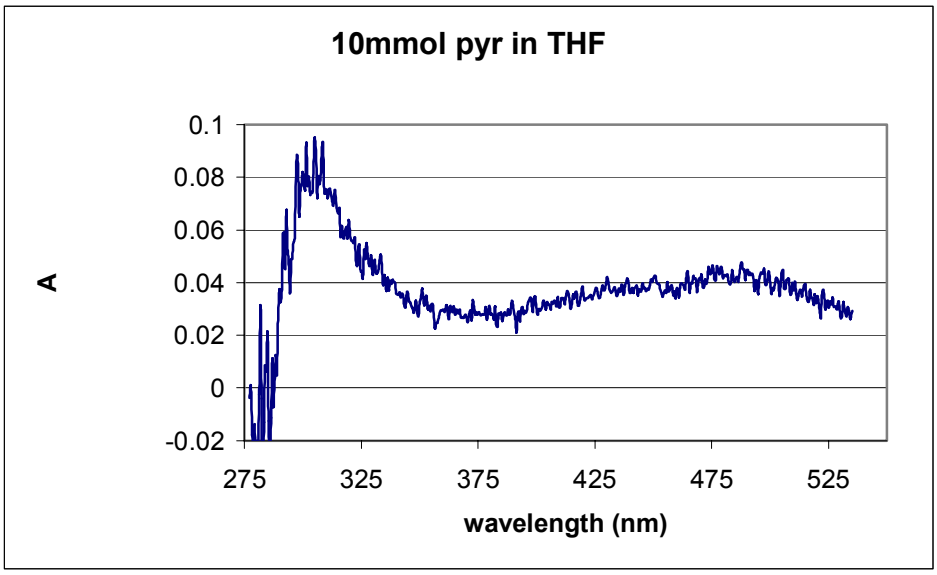


Figure 2.10. Transient absorption spectra produced by LFP of **12** in THF (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window**.**

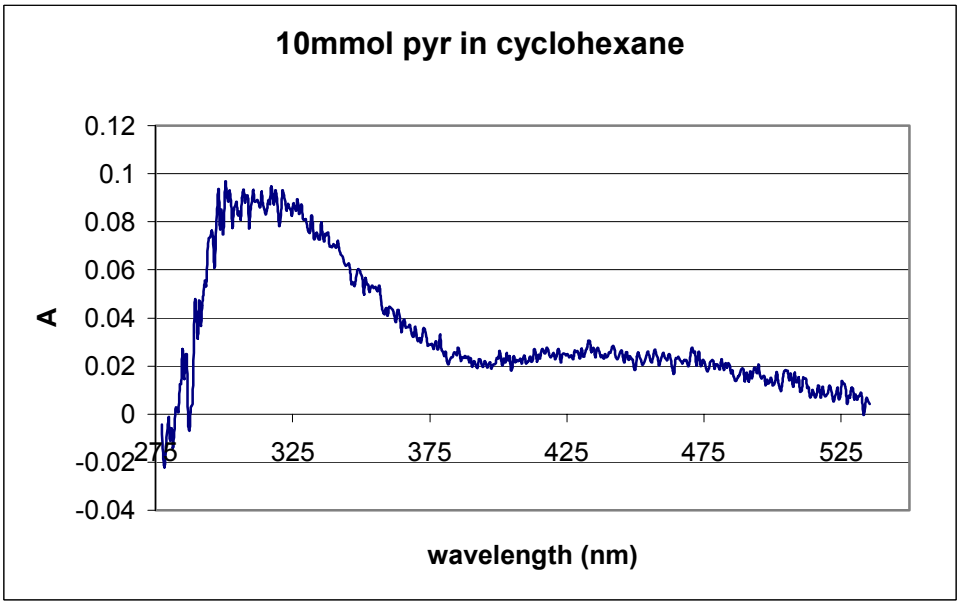


Figure 2.11. Transient absorption spectra produced by LFP of **12** in cyclohexane (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window**.**

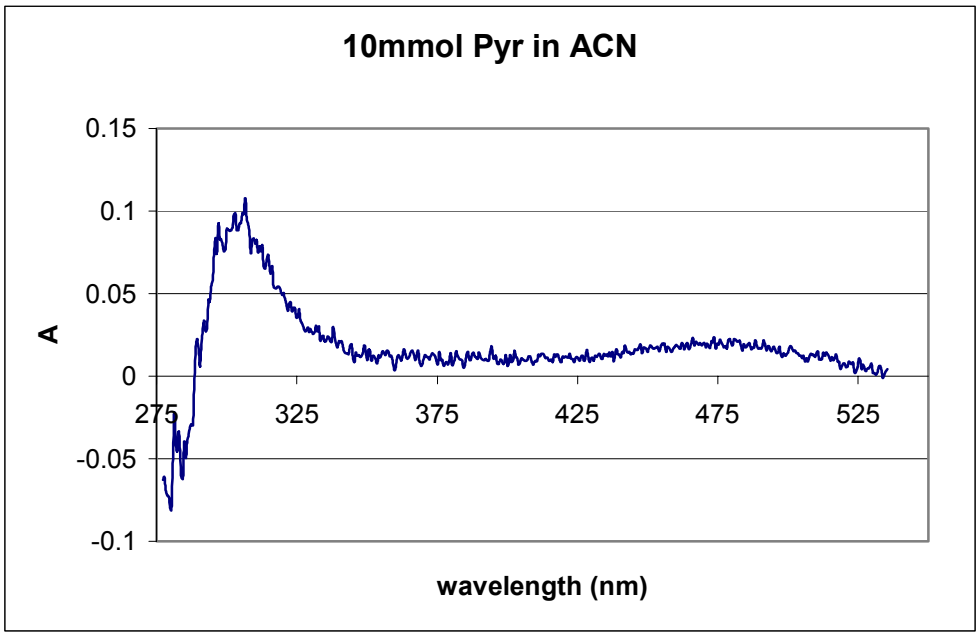
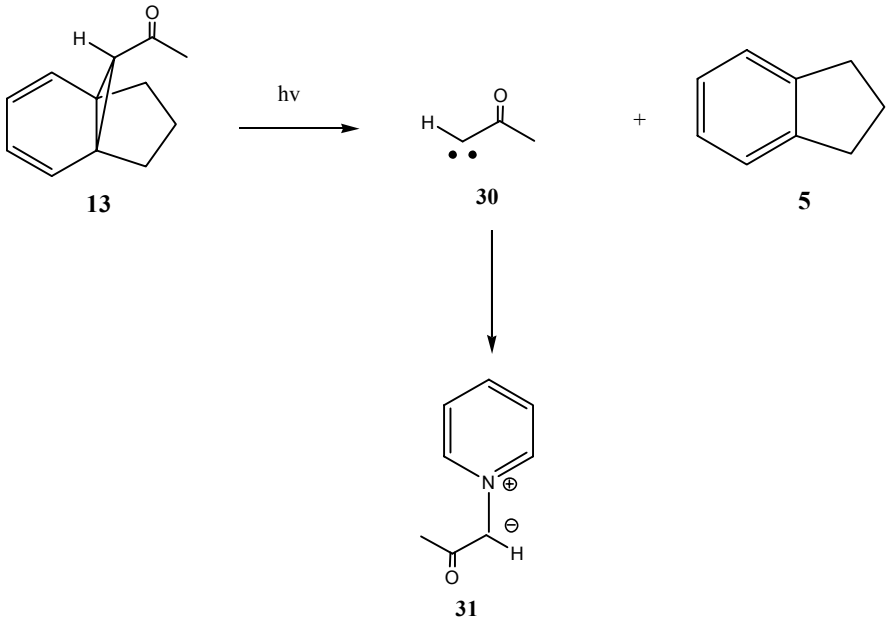


Figure 2.12. Transient absorption spectra produced by LFP of **12** in acetonitrile (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window**.**

2.2.4 Acetylcarbene

LFP studies were preformed at 308 nm with precursor **13** to study acetylcarbene in dichloromethane and THF. 10 mmol pyridine was present in the solvent in order to form ylide **31**. The resulting transient spectra did not show an abosorbance corresponding to the ylide. There was, in fact, a negative absorbance peak, consistent with emission of energy from diene **13**. It is possible that this came from the fluorescence or phosphorescence of the ketone.

A kinetic study of the carbene was performed at 380 nm and the length of the emission was observed to be 0.5 μs.



Scheme 2.9. Reaction of Acetylcarbene.

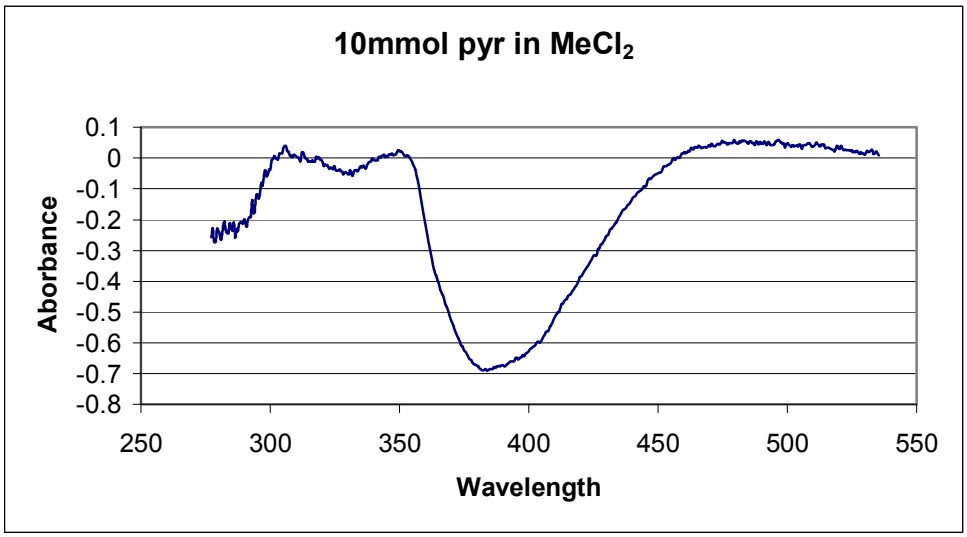


Figure 2.13. Transient absorption spectra produced by LFP of **13** in methylene chloride (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window**.**

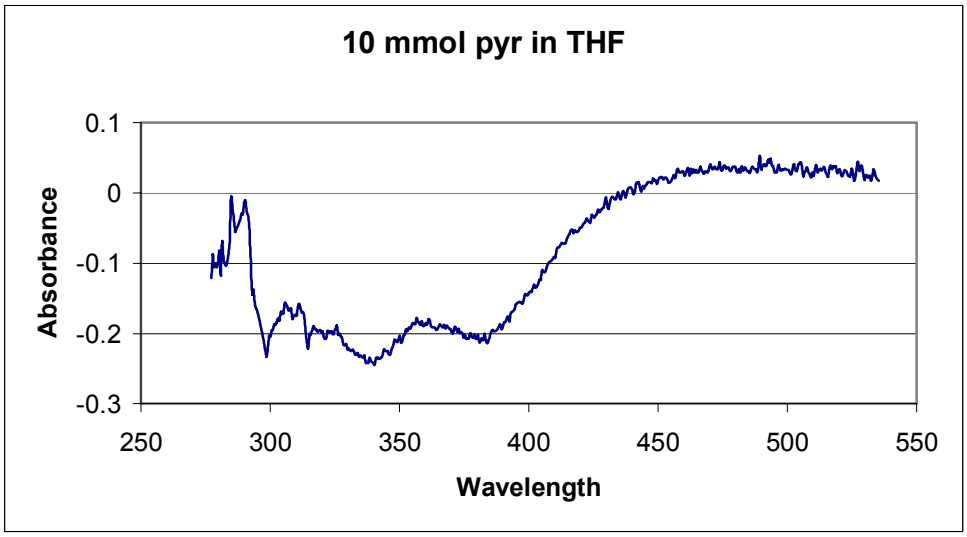


Figure 2.14. Transient absorption spectra produced by LFP of **13** in THF (deoxygenated) at ambient temperature. The spectrum was recorded 50 ns after the 308 nm laser flash over a 20 ns window**.**

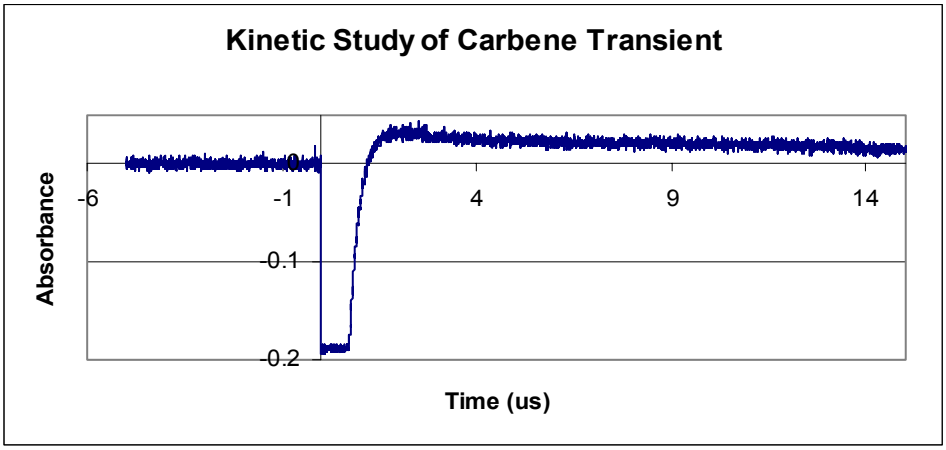
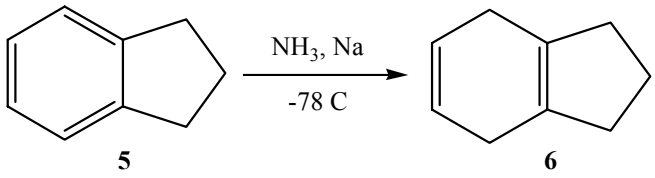


Figure 2.15. Fluorescence produced by LFP of **13**.

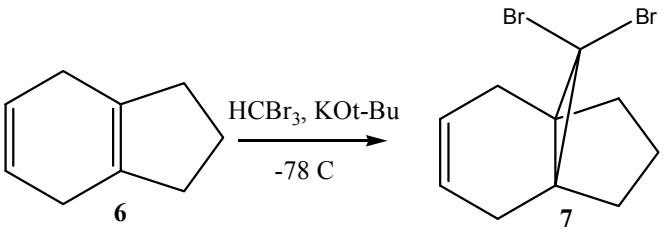
CHAPTER 3

EXPERIMENTAL



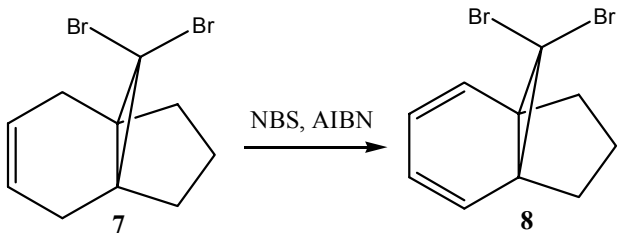
Scheme 3.1. Synthesis of Dihydroindan (**6**).

A 500 mL round bottom flask with a magnetic stir bar and condenser were oven dried, and the apparatus was placed under an inert atmosphere. The flask was placed in an acetone/dry ice bath, and the condenser was also filled with acetone and dry ice. Ammonia was condensed until about 300 mL was present. Indan (**5**) (20 g, 0.17 mol) and absolute methanol were added to the flask and allowed to stir. 1-2 g portions of sodium (7.7 g, 0.36 mol) were added to maintain a blue reaction color at all times. The reaction was allowed to stir overnight and the ammonia evaporated. Ethanol was added to quench any remaining sodium, and then water was added to the flask. The mixture was extracted with hexane. The organic layers were washed with water, dried, filtered, and condensed. The product was purified on silica gel with hexane elution. The hexane was evaporated to give the product (18.5 g, 91 % yield, 95 % dihydroindan). ^{1}H NMR ($CDCl_3$) δ_H 5.65 (s, 2 H), 2.55 (s, 4 H), 2.17 (t, 4 H, J = 7.5 Hz), 1.80-1.69 (m, 2 H). ^{13}C NMR ($CDCl_3$) δ_C 132.21, 125.15, 35.96, 27.99, 21.84. IR (neat) 3023.9, 2948.8, 2841.0, 1649.0, 1459.0, 1443.9 cm^{-1}.



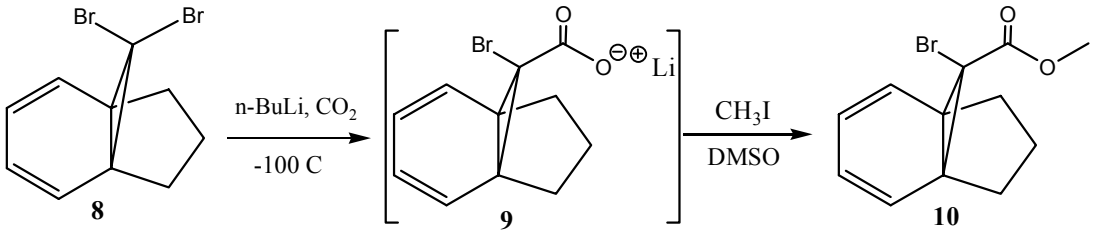
Scheme 3.2. Synthesis of 10,10-dibromo-tricyclo[4,3,1,0]deca-3-ene (**7**).

A 1000 mL round bottom flask with a magnetic stir bar was oven dried, and placed under positive nitrogen pressure. Dry pentane was added to the flask. Dihydroindan (**6**) (7.20 g, 0.06 mol) and potassium t-butoxide (4.77 g, 0.043 mol) were added to the flask which was in an acetone/dry ice bath. Bromoform (3.72 mL, 0.043 mol) was added dropwise via syringe to the reaction over 4 h. The mixture was allowed to warm to room temperature and stir overnight. The reaction mixture was cooled to 0 °C and water was added. The mixture was filtered through 5.0 g of Celite and placed into a 500 mL flask. Three-quarters of an equivalent of KOt-Bu was added to the flask and it was allowed to stir for 30 min. Water was added to the flask and the solution was washed with saturated ammonium chloride and water. The organic layer was dried, filtered, and concentrated. A white solid was formed, and purified on a silica column to give the desired product (1.6 g, 90 % yield). TLC was used to check the purity of the desired product. R_f 0.6 (hexane). ^{1}H NMR ($CDCl_3$) δ_H 5.45 (s, 2 H), 2.29-2.16 (m, 6 H), 2.03-1.97 (m, 2 H), 1.66-1.58 (m, 2 H). ^{13}C NMR ($CDCl_3$) δ_C 123.96, 56.41, 39.99, 37.35, 28.96, 26.70. IR (Nujol) 2929.6, 2896.5, 1426.5, 1323.3 cm $^{-1}$.



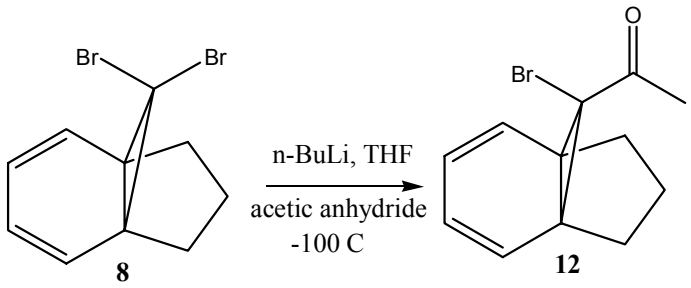
Scheme 3.3. Synthesis of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (**8**).

To a 1000 mL round bottom flask, with magnetic stir bar, was added 10,10-dibromo-tricyclo[4.3.1]deca-3-ene (**7**) (2.5 g, 8.5 mmol) and 250 mL cyclohexane. NBS (3.12 g, 17.5 mmol) and AIBN (0.034 g, 0.021 mmol) were also added. The reaction was heated at reflux for 3 h. Then the mixture was allowed to cool and the solution was filtered through celite. The solution was then washed with water. The organic layer was dried, filtered, evaporated, and run on a silica column using hexane as eluent. TLC was used to check the purity of the fractions. Those fractions that contained only a single spot with an R_f of 0.35 (hexane) were combined and condensed to yield the product (0.40 g, 85 % yield) with a melting point of 79 °C – 82 °C. ^{1}H NMR ($CDCl_3$) δ_H 6.14 (dd, 2 H, *J* = 2.35 Hz, 9.3 Hz), 5.84 (dd, 2 H, *J* = 2.2 Hz, 7.4 Hz), 2.41 (m, 3), 2.11 (m, 4 H), 1.72 (m, 4 H). ^{13}C NMR ($CDCl_3$) δ_C 124.04, 123.56, 48.68, 37.25, 24.89 . IR (Nujol) 2922.9, 2852.8, 1461.4, 1376.5 cm $^{-1}$.



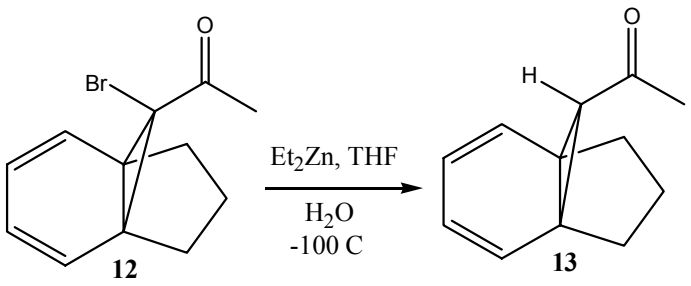
Scheme 3.4. Synthesis of 10-endo-bromo-10-exo-carbomethoxytricyclo[4,3,1,0]-deca-2,4-diene (**10**).

200 mgs of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (8) were added to an oven dried 50 mL round-bottom flask. 20 mL of freshly distilled THF was added via syringe. The flask was placed in a methanol/liquid nitrogen bath. 1.6 mL of n-BuLi was added via syringe and the reaction was allowed to stir for 1 h at -100 ºC. Crushed dry ice was added to the reaction flask, and it was allowed to warm to room temperature. The solution was condensed and the solid was washed with ice-cold ether. The salt was dissolved in 25 mL of dry DMSO. 0.06 mL of CH_3I was added, and the mixture stirred at room temperature for 30 min. The solution was poured into ice water, extracted with ether, washed with water and brine, and dried. Charcoal was used to remove the color from the solution, and it was filtered and condensed to yield a white solid (160 mg, 80% yield). ^{1}HNMR (CDCl3) δ_H 6.14 (dd, 2 H, J = 2.35 Hz, 9.3 Hz), 5.84 (dd, 2 H, J = 2.2 Hz, 7.4 Hz),3.82 (s, 3 H), 2.41 (m, 3 H), 2.11 (m, 4 H), 1.72 (m, 4 H). IR (Neat) 3036.77, 2952.2, 1736.69, 1383.81, 1294.44, 1273.06 cm^{-1}.



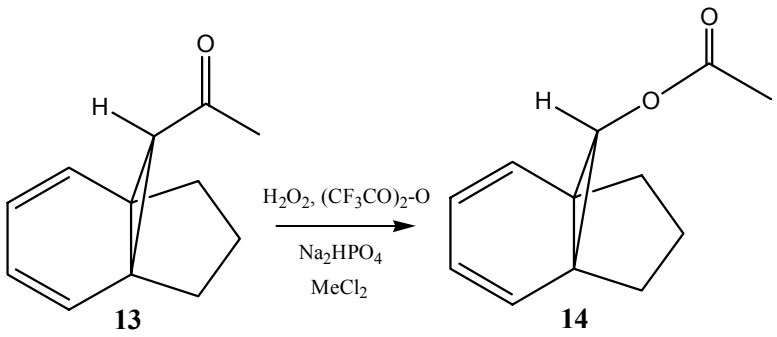
Scheme 3.5. Synthesis of
10-endo-bromo-10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene (**12**).

To an oven dried 100 mL RBF, 100 mg of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (**8**) was added under argon. 20 mL of distilled THF was added via syringe and the flask was cooled in a methanol/liquid N_2 bath to –100 ºC. 0.64 mL of n-BuLi was added via syringe. The mixture turned a light brown color, and it was allowed to stir for 45 min at –100 ºC. 0.036 mL of acetic anhydride, distilled over CaH_2, was added drop-wise via syringe, and was allowed to stir for 4 h while it warmed to room temperature. The reaction mixture was poured into ice water, extracted with ethyl acetate, washed three times with 3.55M NaOH, and brine. The organics were dried over $MgSO_4$ and evaporated to yield a yellow liquid. This was purified on a silica column using hexane as an eluent. Those fractions containing a single spot on the TLC with an R_f of 0.24 (hexane) were combined and concentrated to yield the product (0.044g, 50% yield). ^1H NMR ($CDCl_3$) δ_H 6.14 (dd, 2 H, J=2.35 Hz, 9.3 Hz), 5.84 (dd, 2 H, 2.2 Hz, 7.4 Hz), 3.52 (s, 3 H), 2.41 (m, 3 H), 2.11 (m, 4 H), 1.72 (m, 4 H). IR (Neat) 3033.8, 2931.51, 1706.62, 1377.1 cm^{-1}.



Scheme 3.6. Synthesis of 10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene (**13**).

To an oven dried 100 mL RBF add 50 mg of 10-endo-bromo-10-exo-carbomethyltricyclo[4,3,1,0]-deca-2,4-diene (**12**) under argon. 20 mL of distilled THF was added and the flask was cooled to –100 ºC in a methanol/liquid nitrogen bath. At this point 0.22 mL of 1.0M Et_2Zn in THF was added via syringe and it was allowed to stir for 30 min. The flask was warmed to –20 ºC, excess water was added to the reaction mixture via syringe, and it was stirred for 30 min at room temperature. The mixture was washed with 1M HCl and extracted with ethyl acetate. The organic layer was washed with brine, dried over $MgSO_4$, and concentrated. The solid was purified using a silica column using hexane as an eluent. TLC was used to confirm the purity of the fractions. Those fractions with a single spot at an $R_f = 0.60$ (hexane) were combined and condensed to yield a white solid (0.021g, 60% yield). ^{1}H NMR ($CDCl_3$) δ_H 6.14 (dd, 2 H, J=2.35 Hz, 9.3 Hz), 5.84 (dd, 2 H, 2.2 Hz, 7.4 Hz), 3.52 (s, 3 H), 3.26 (d, 1 H), 2.41 (m, 3 H), 2.11 (m, 4 H), 1.72 (m, 4 H).



Scheme 3.7. Synthesis of 10-exo-acetatetricyclo[4,3,1,0]-deca-2,4-diene (**14**).

To a 100 mL RBF 14.8 mg of 10-exo-acetyltricyclo[4,3,1,0]-deca-2,4-diene were dissolved in 20 mL of methylene chloride. 132 mg of Na_2HPO_4 was added to the mixture and allowed to stir for 5 min. To a 50 mL RBF 9.69 µL of 50 % H_2O_2 and 68.7 µL of trifluoroacetic anhydride were added and stirred for 5 min. The H_2O_2/trifuoroacetic anhydride mixture was added to the reaction flask and allowed to stir for 24 h. The mixture was washed with 3.55M NaOH and extracted with ethyl acetate. The purity of the sample was checked with TLC and a new spot with an R_f value of 0.42 (hexane) was observed.

APPENDIX A

General Methods. All the chemical reagents used were purchased from Sigma Aldrich. NMR spectra were obtained on a Brucker DPX-400 MHz spectrometer. IR spectra were obtained on a Perkin Elmer FT-IR Spectrum 2000 spectrometer.

Laser Flash Photolysis. For LFP experiments, all precursor solutions were prepared such that the optical density at the excitation wavelength was 1-1.5. The LFP system used a Lambda Physik LPX-100 excimer (308 nm). The transient absorption spectra were collected using an EG&G PARC 1460 optical multichannel analyzer with an EG&G 1304 PARC pulse amplifier, EG&G PARC 1024 UV detector, and a Jarrell-Ash 1234 grating.

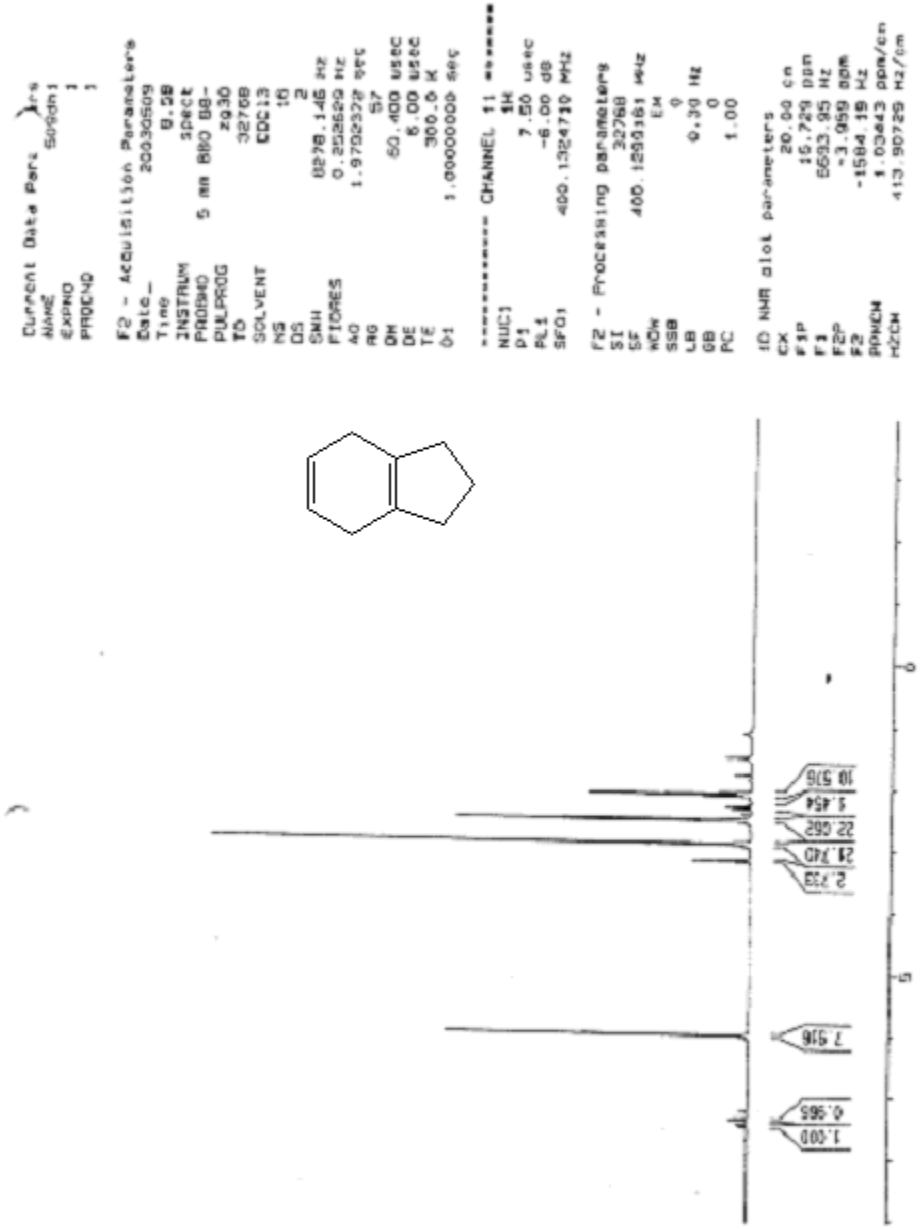


Figure A.1. ^{1}H NMR Spectrum of dihydroindan (**6**).

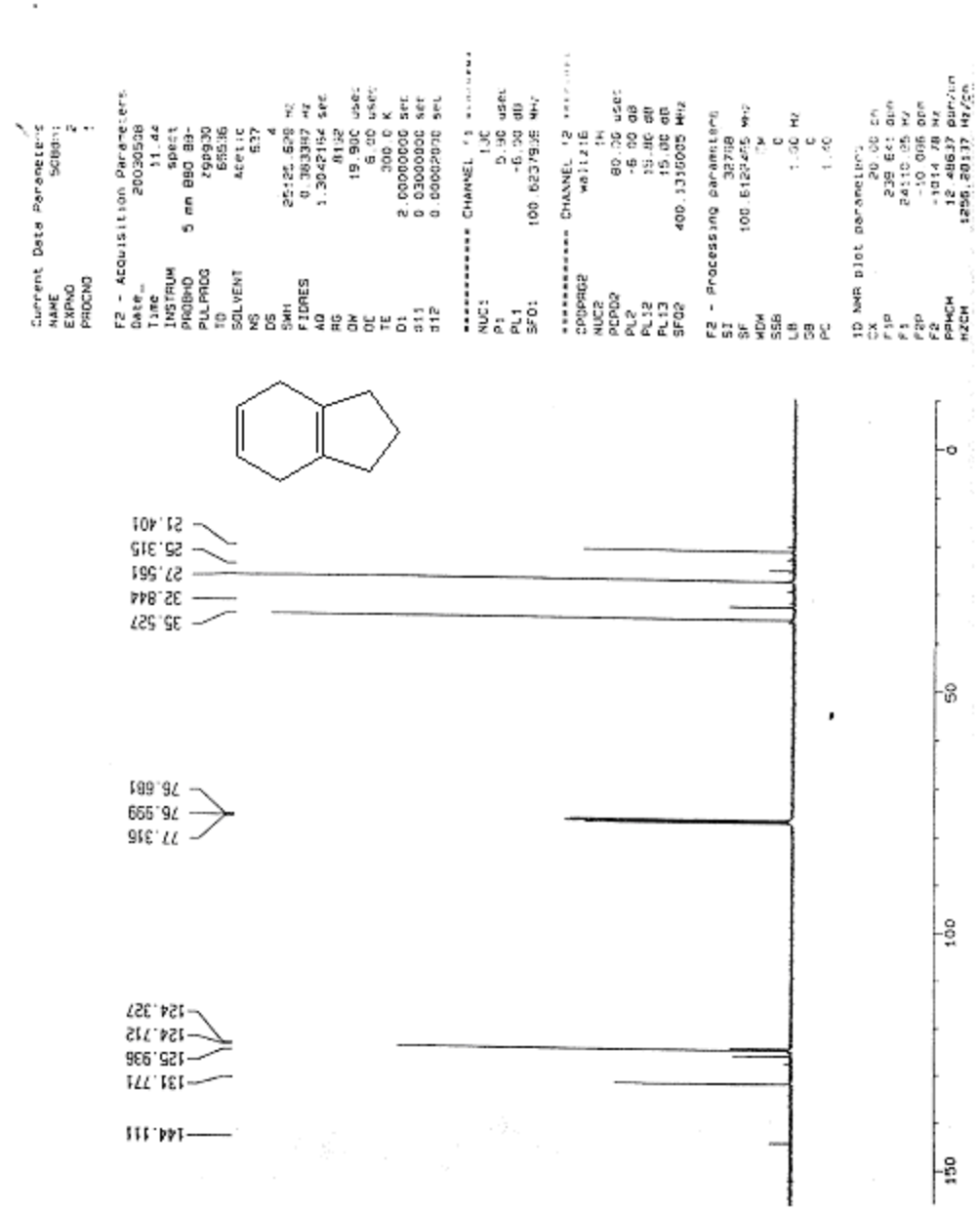


Figure A.2. ^{13}C Spectrum of dihydroindan (**6**).

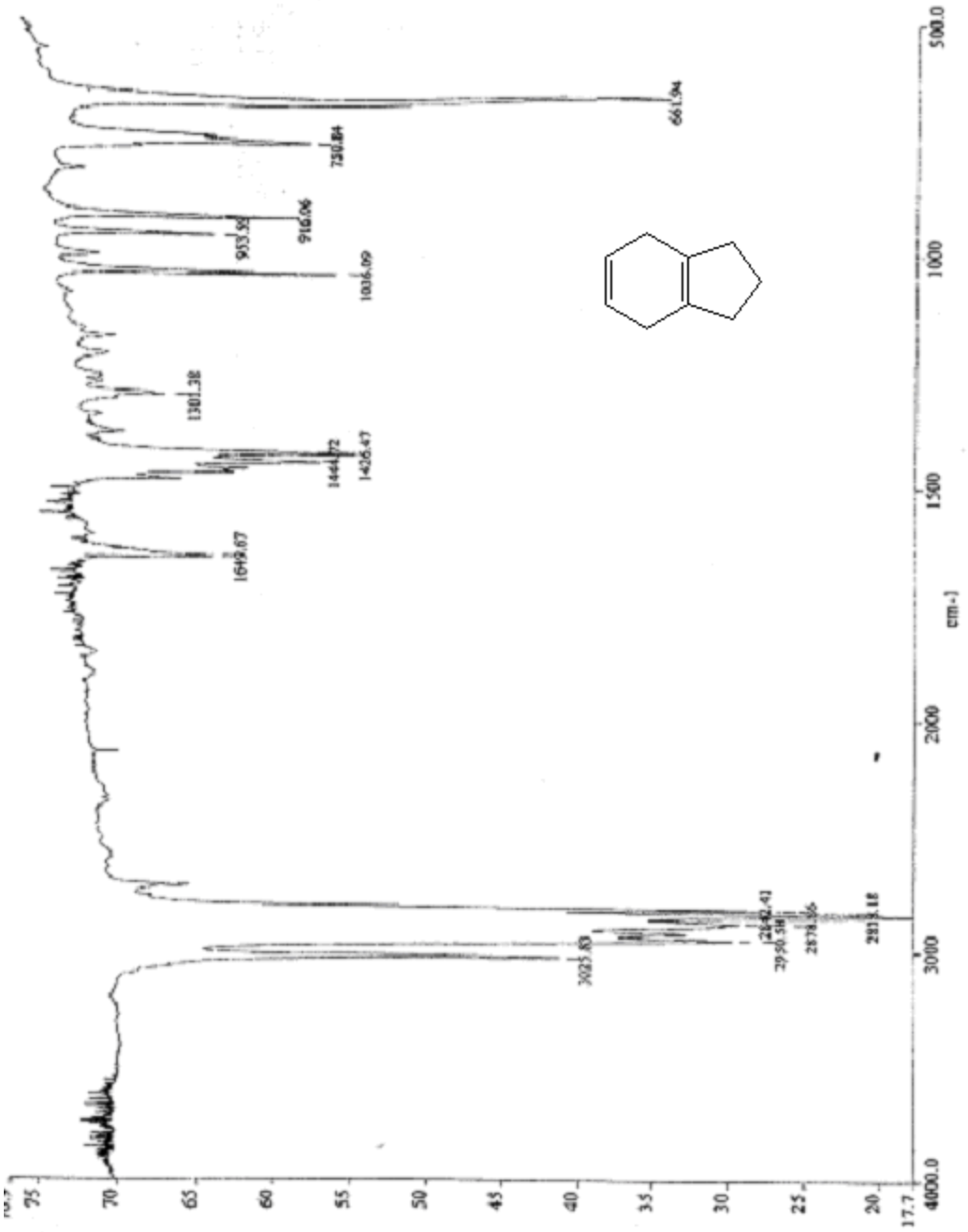


Figure A.3. IR Spectrum of dihydroindan (**6**).

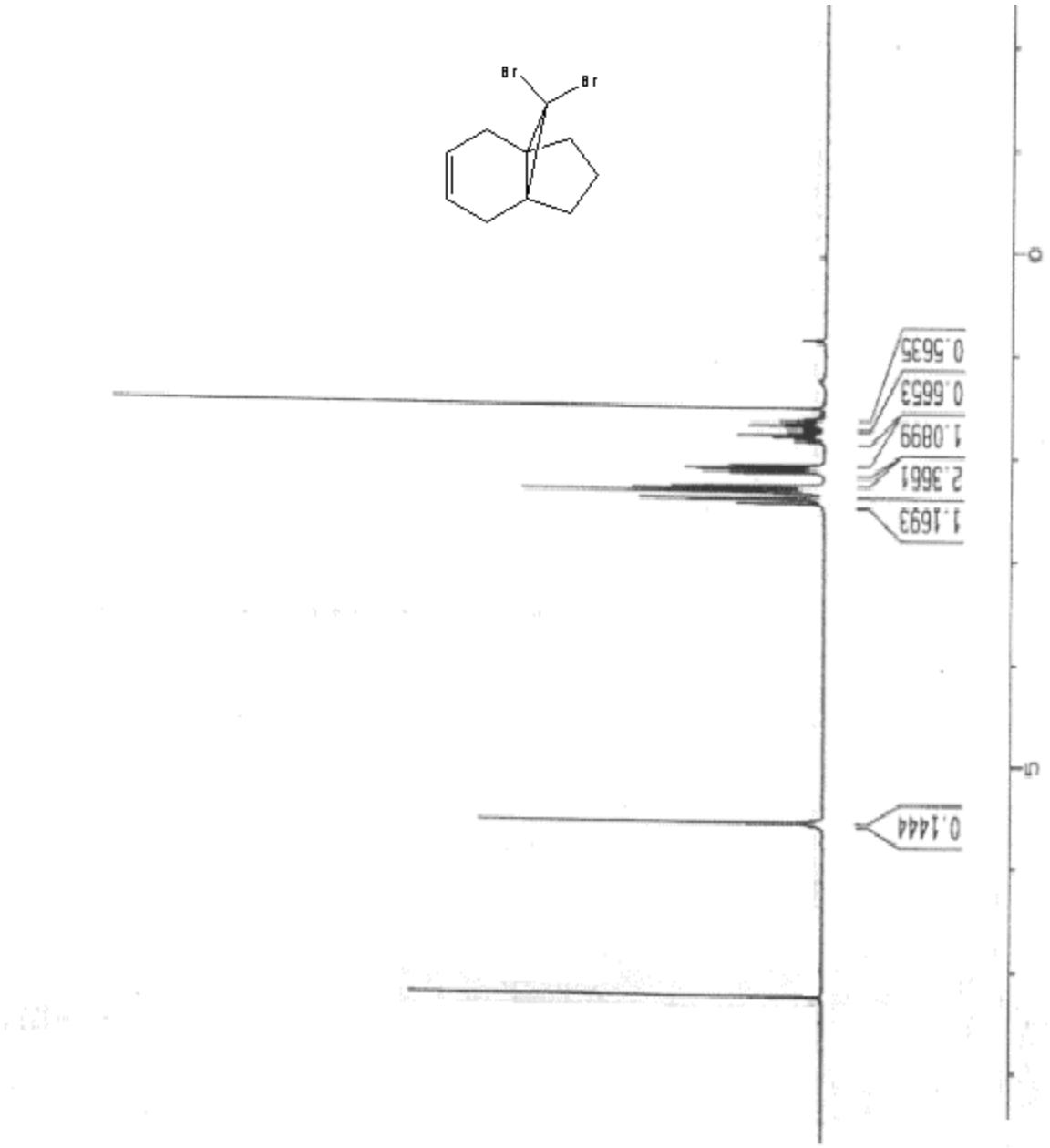


Figure A.4. ^{1}H NMR Spectrum of 10,10-dibromo-tricyclo[4,3,1,0]deca-3-ene (**7**).

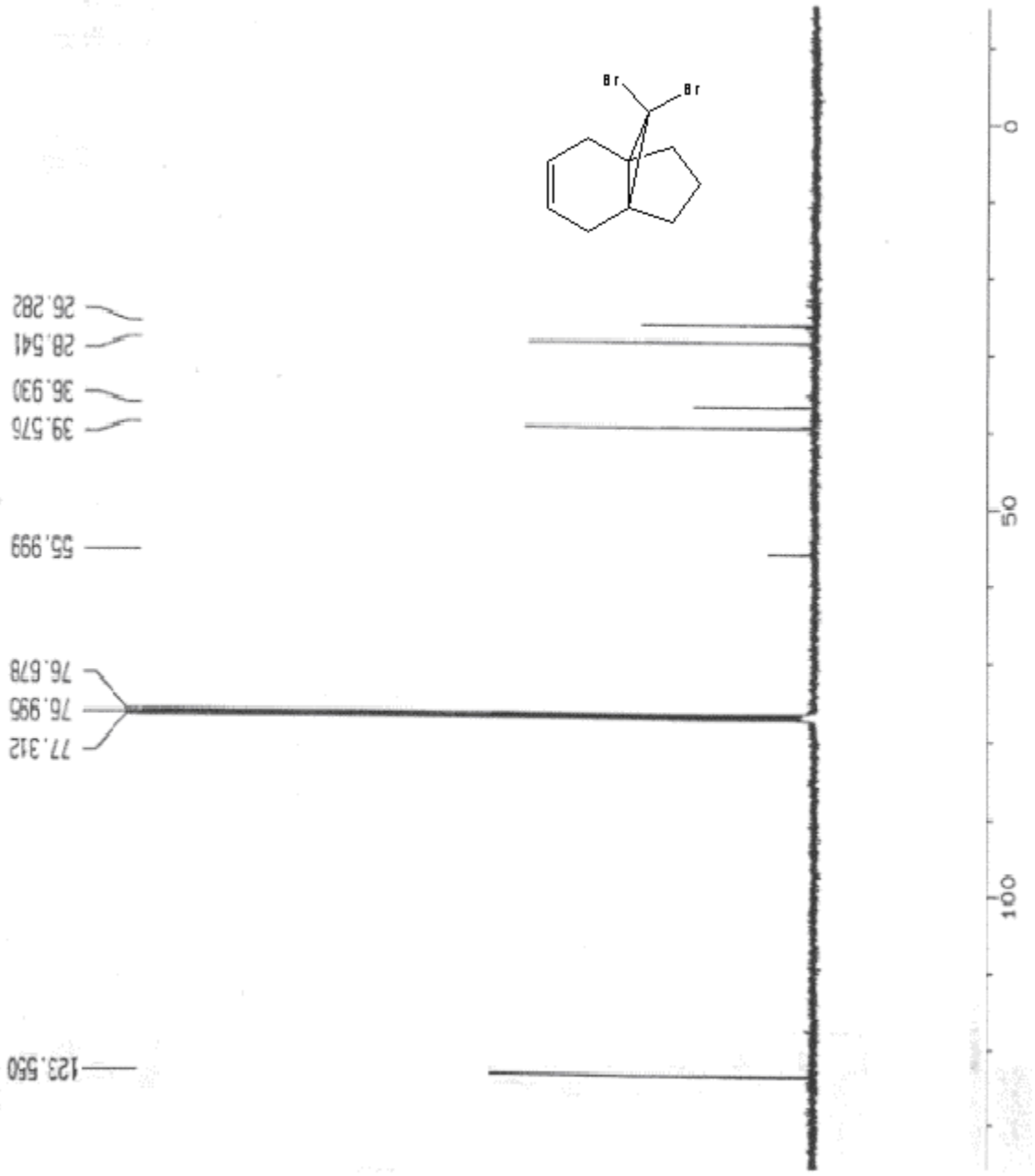


Figure A.5. ^{13}C NMR Spectrum of 10,10-dibromo-tricyclo[4,3,1,0]deca-3-ene(**7**).

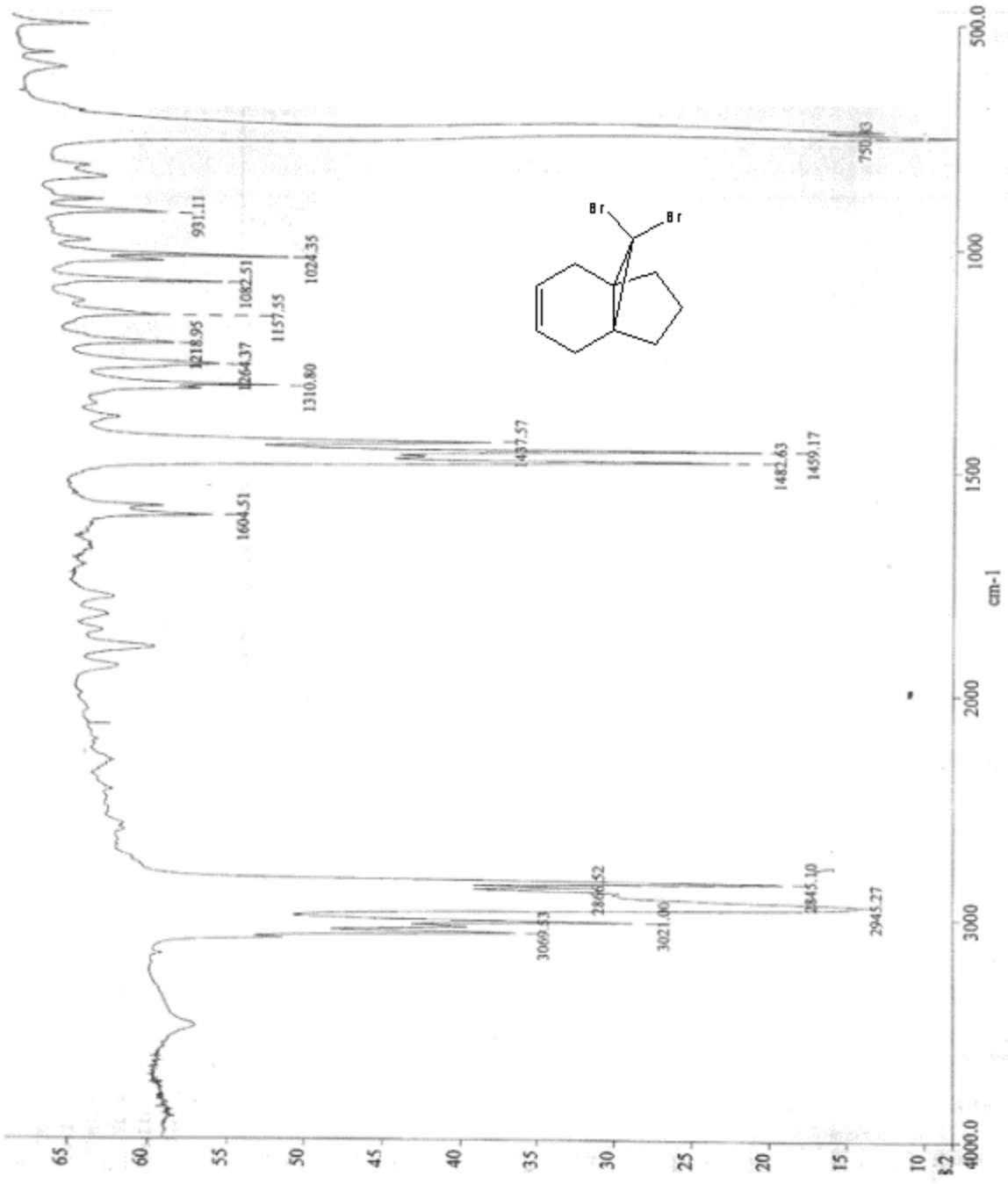


Figure A.6. IR Spectrum of 10,10-dibromo-tricyclo[4,3,1,0]deca-3-ene(**7**).

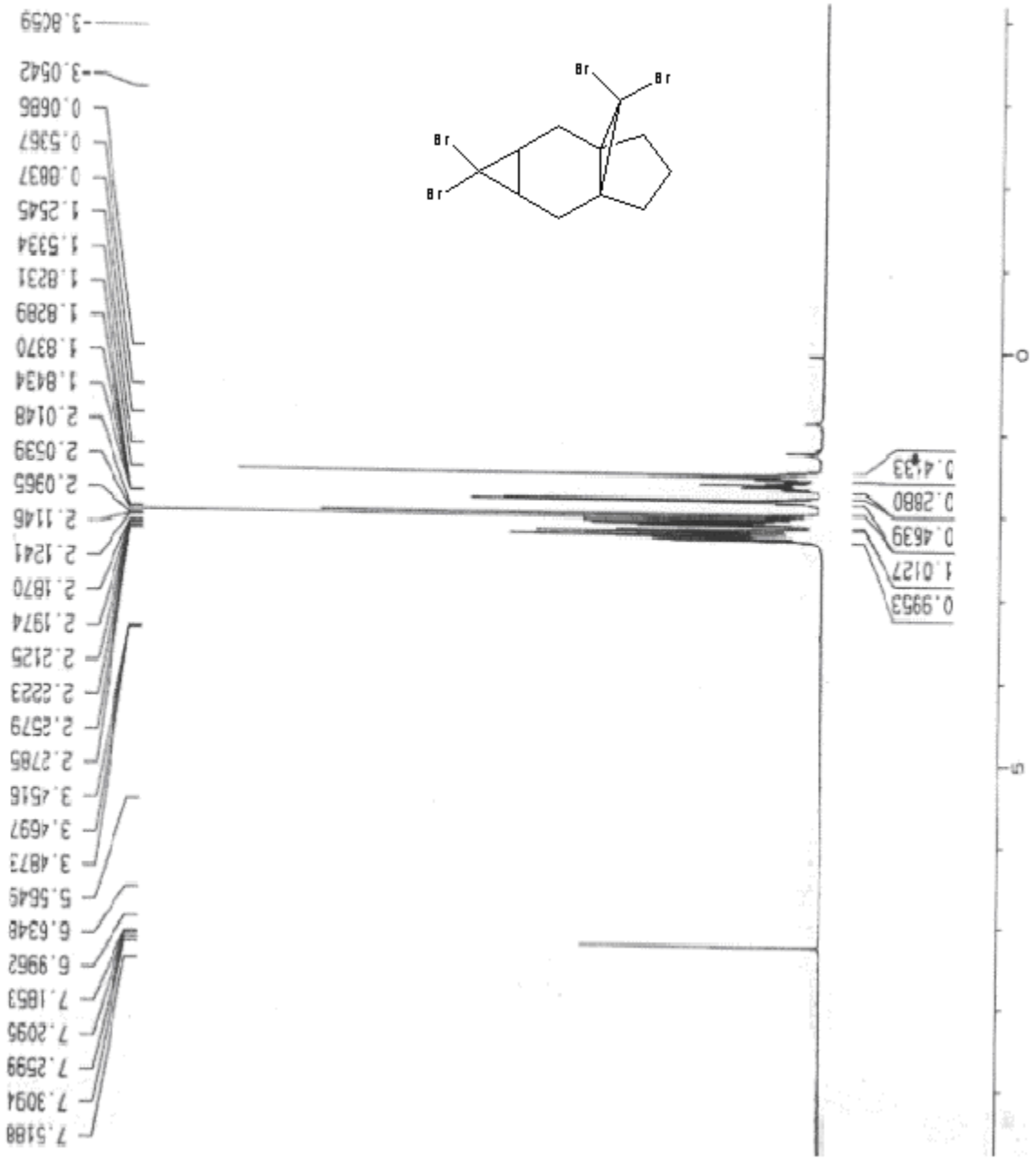


Figure A.7 ^{1}H NMR Spectrum of tetra-brominated product (**11**).

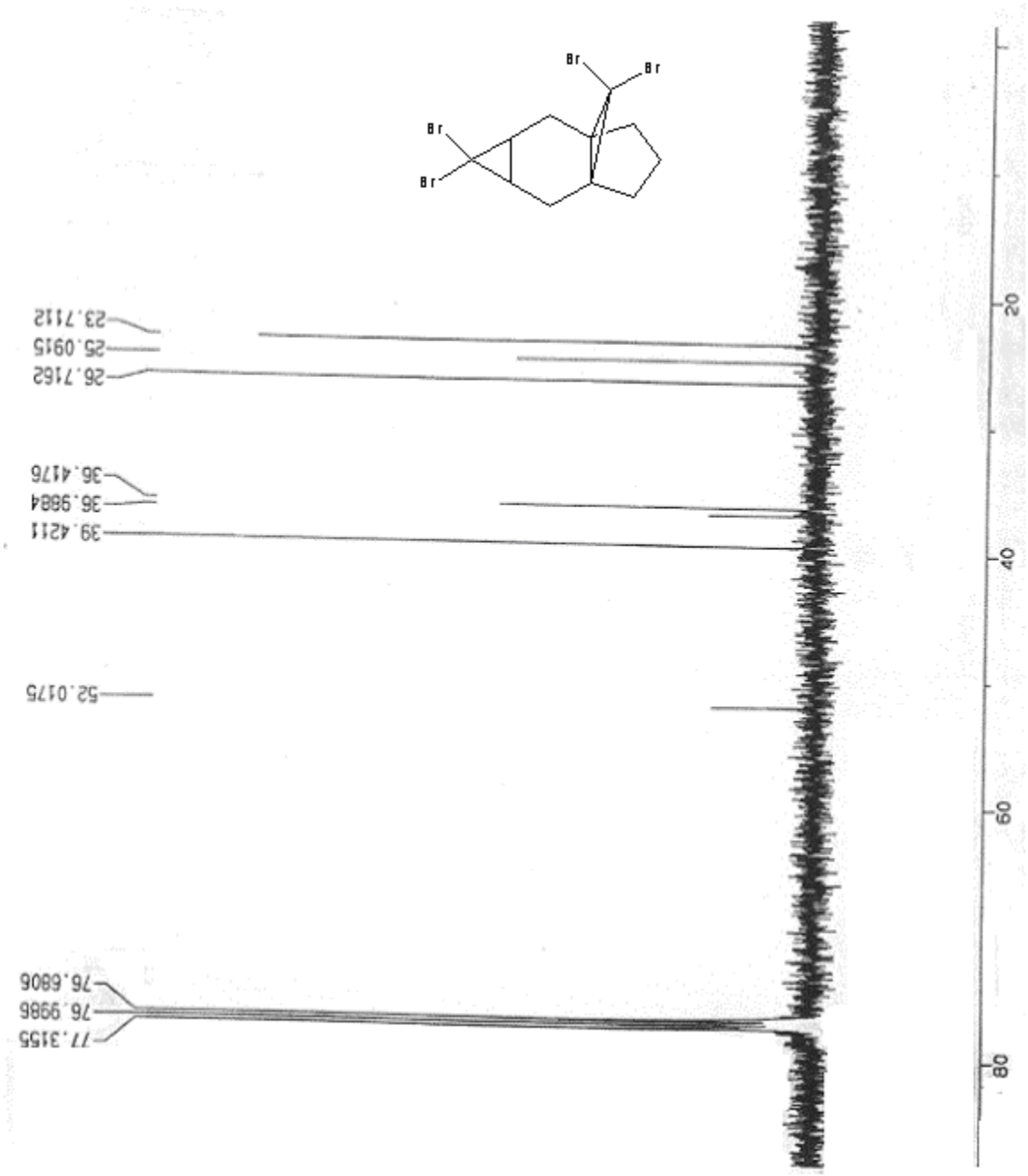


Figure A.8. ^{13}C NMR Spectrum of tetra-brominated product (**11**).

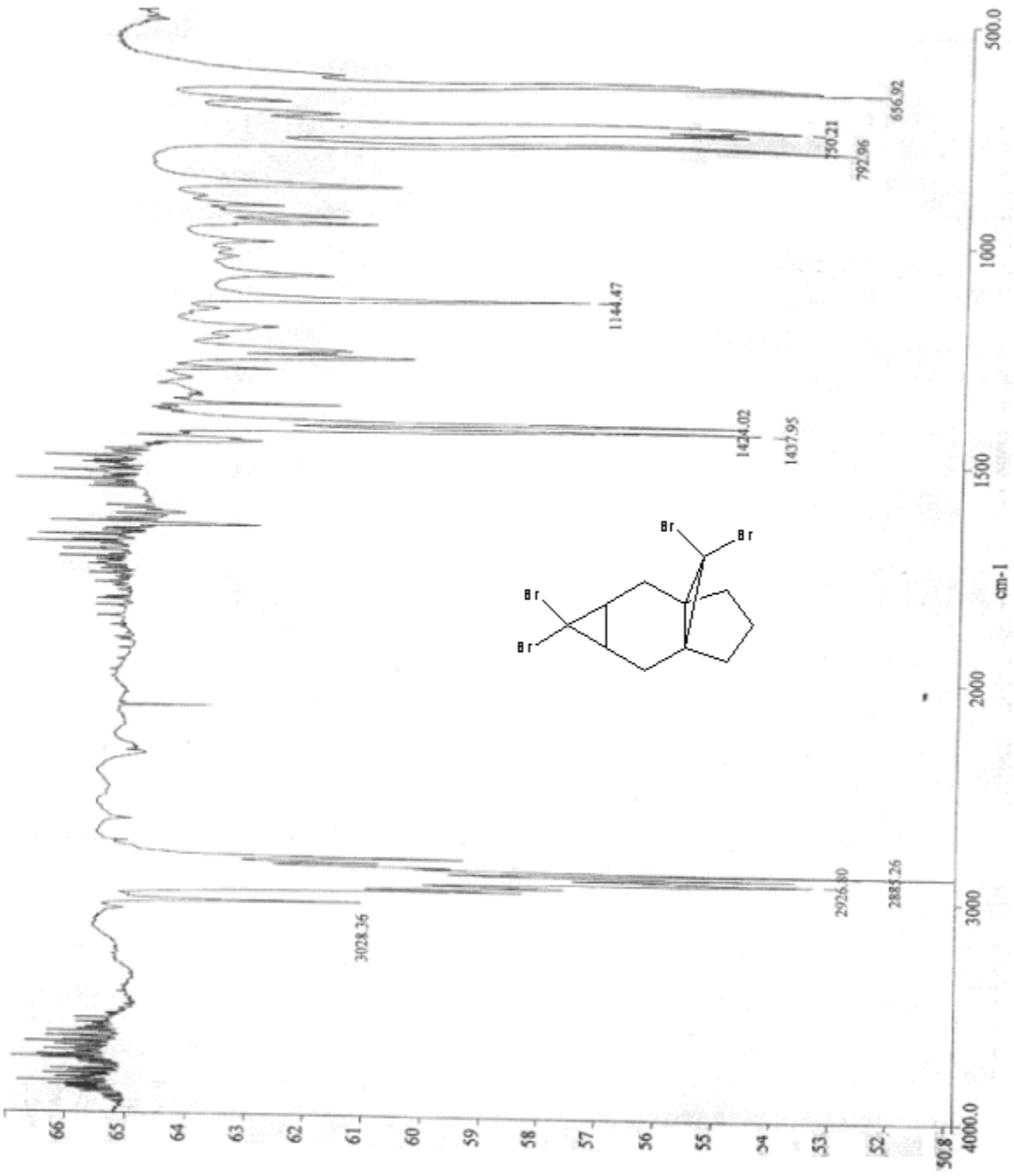


Figure A.9. IR Spectrum of tetra-brominated product (**11**).

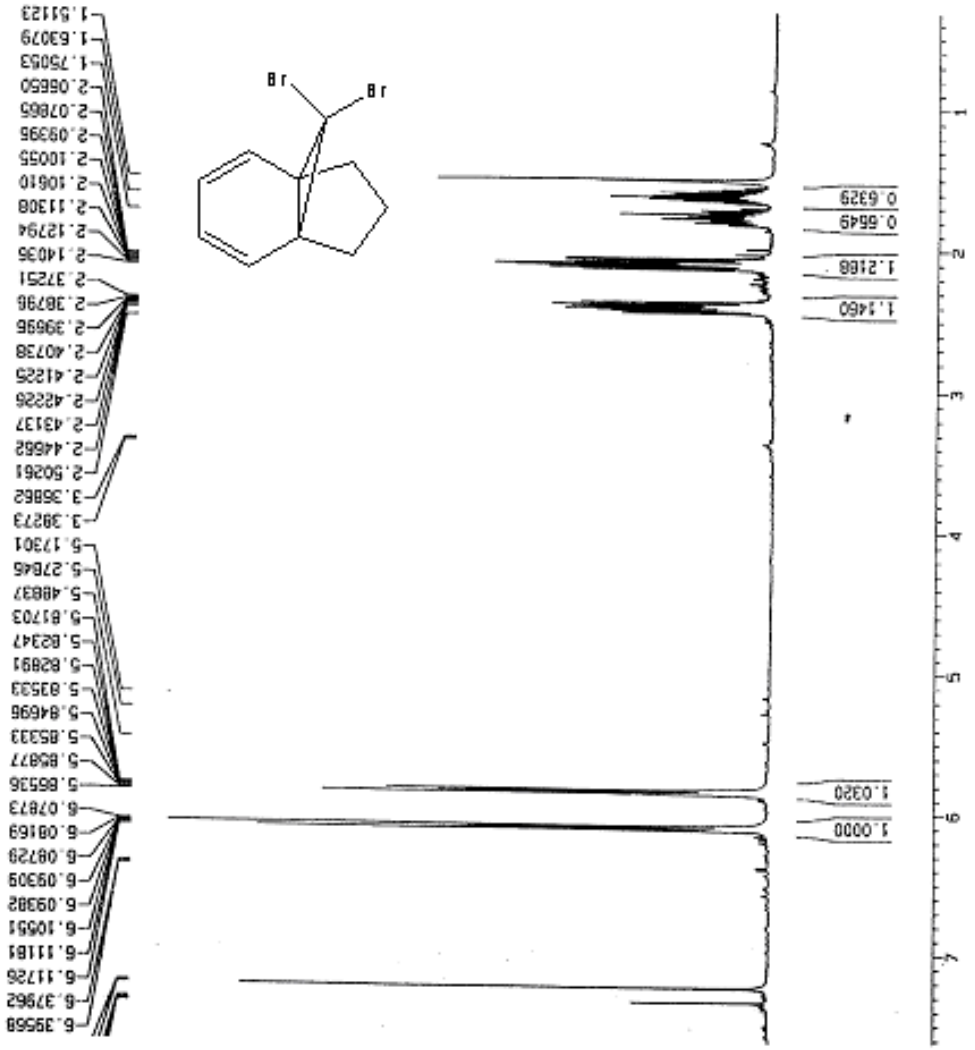


Figure A.10. ^{1}H NMR Spectrum of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (**8**).

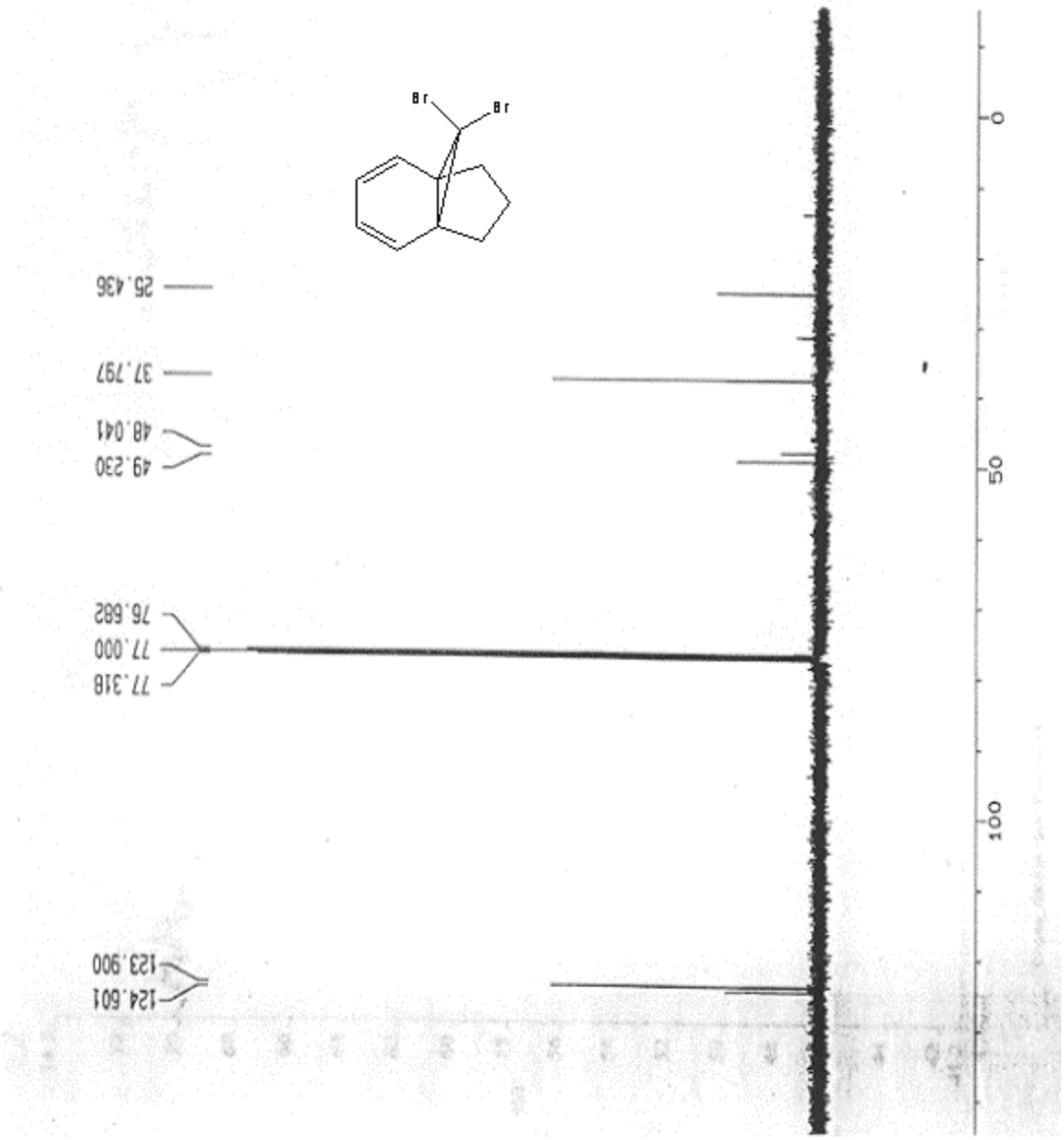


Figure A.11. ^{13}C NMR Spectrum of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (**8**).

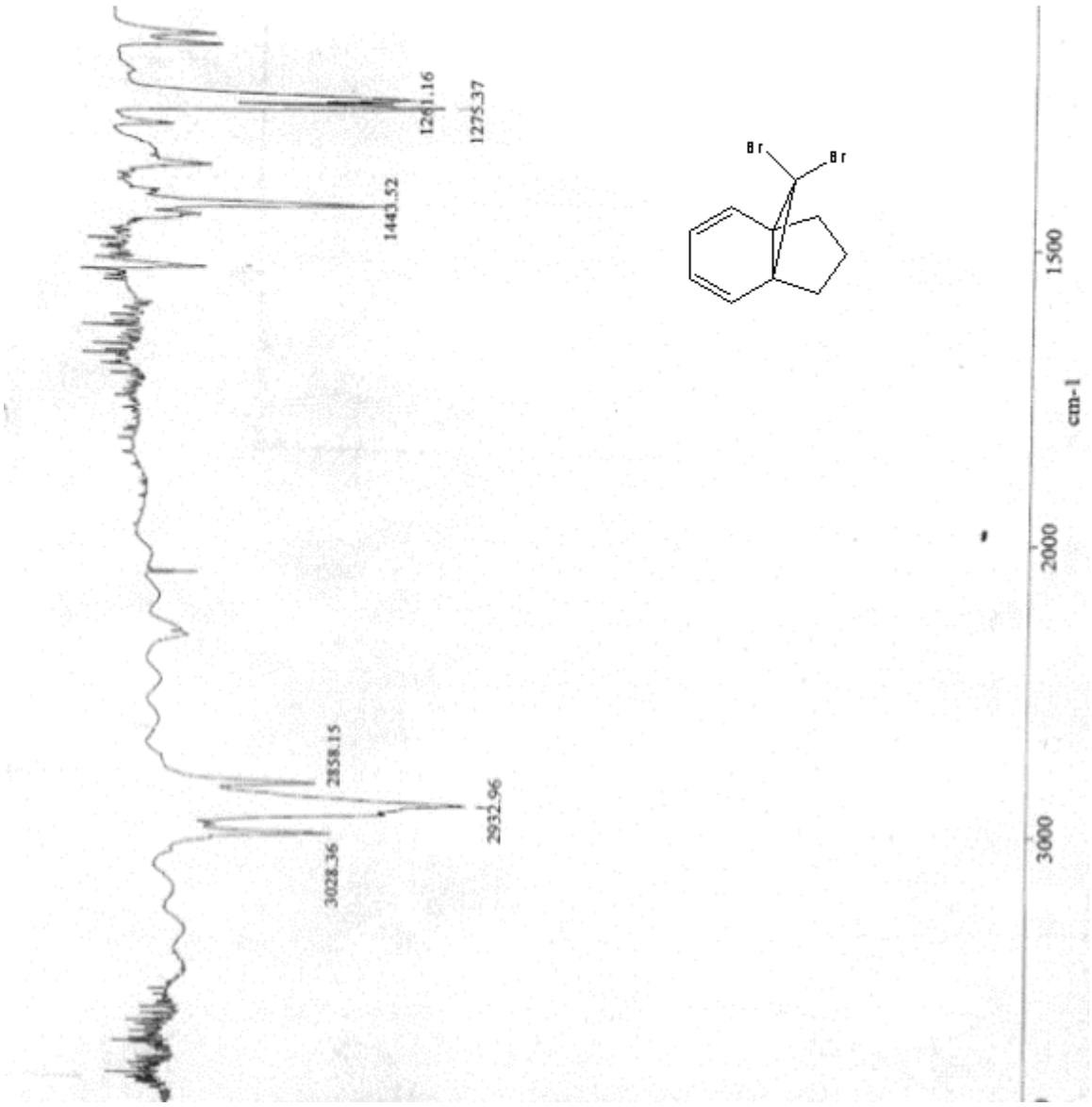


Figure A.12. IR Spectrum of 10,10-dibromo-tricyclo[4.3.1.0]deca-2,4-diene (**8**).

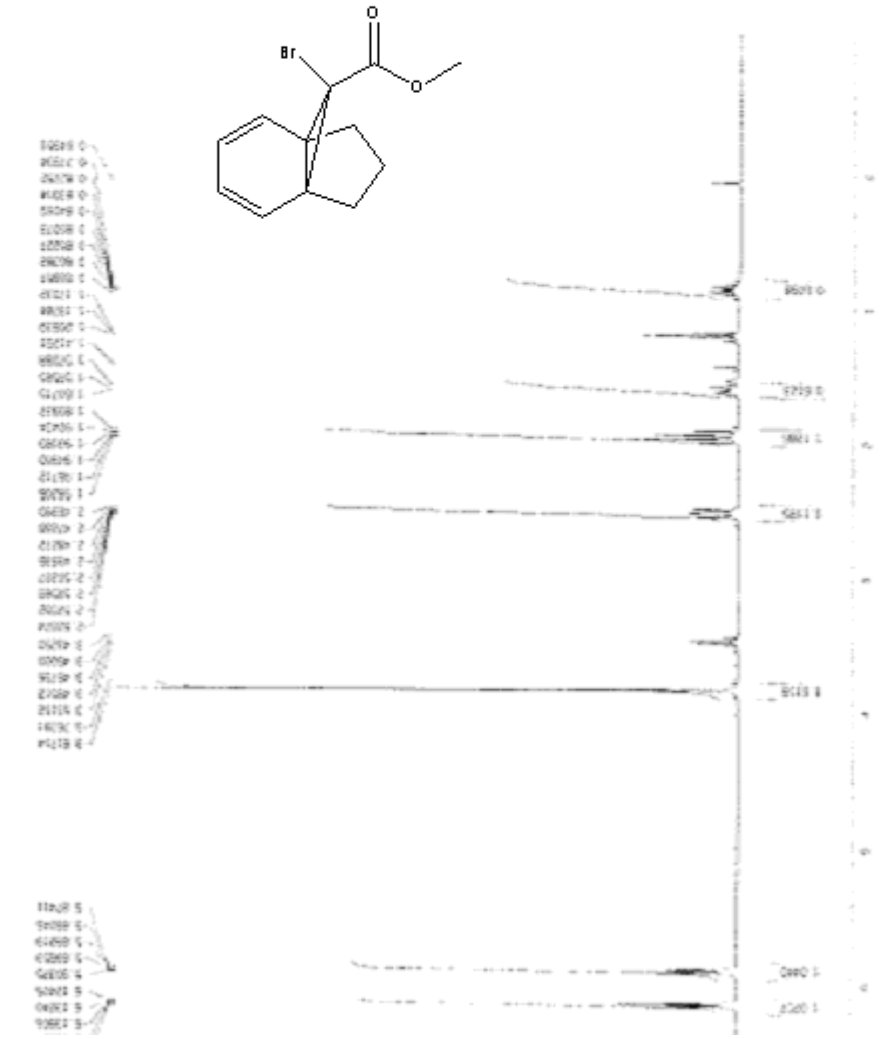


Figure A.13. ^{1}H NMR Spectrum of of 10-endo-bromo-10-exo-carbomethoxytricyclo[4,3,1,0]-deca-2,4-diene (**10**).

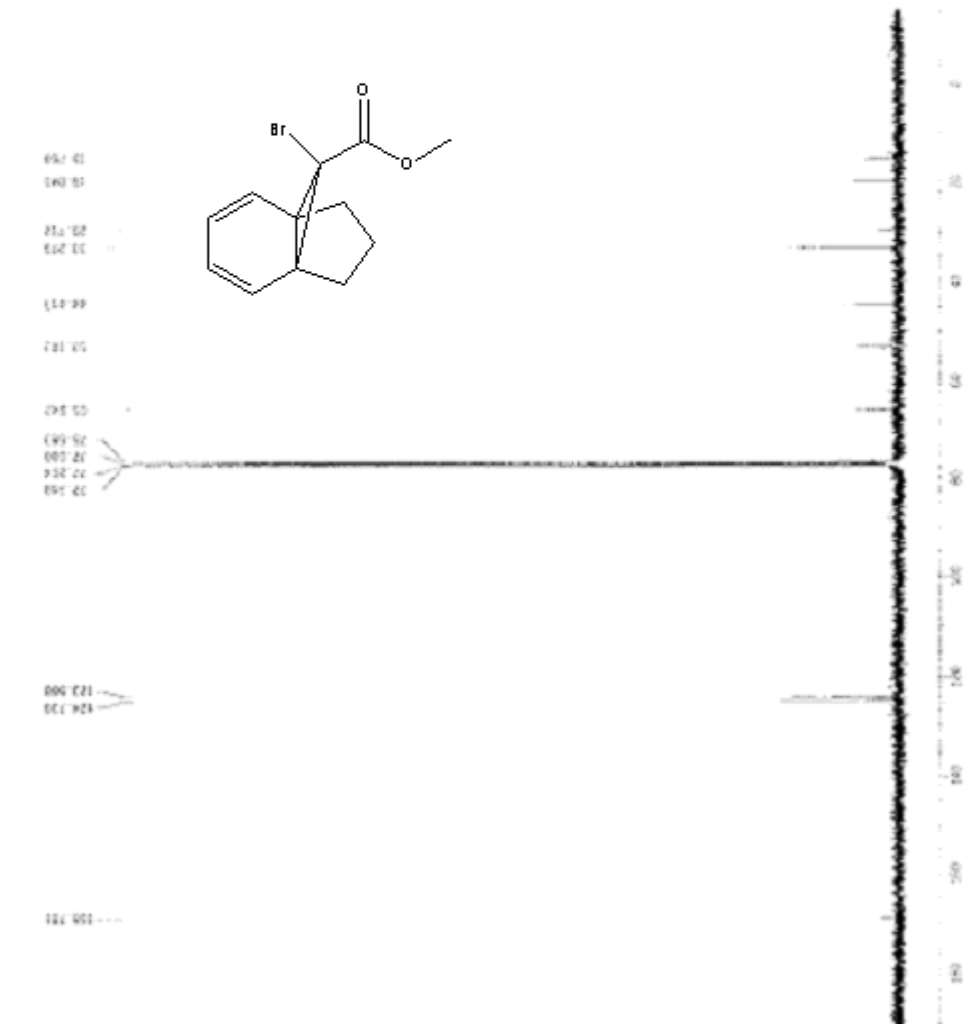


Figure A.14. ^{13}C NMR Spectrum of 10-endo-bromo-10-exo-carbomethoxytricyclo[4,3,1,0]-deca-2,4-diene (**10**).

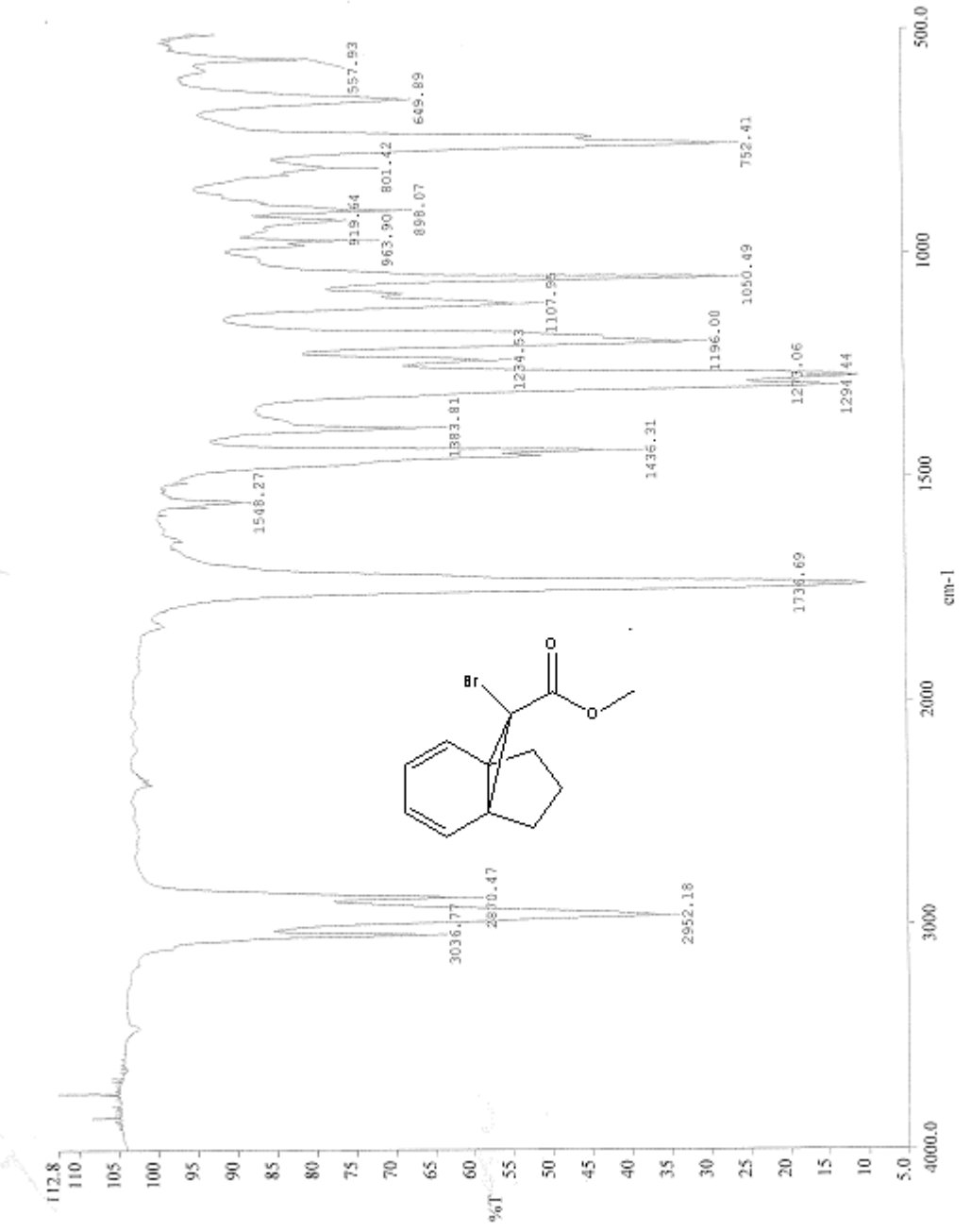


Figure A.15. IR Spectrum of 10-endo-bromo-10-exo-carbomethoxytricyclo[4,3,1,0]-deca-2,4-diene (**10**).

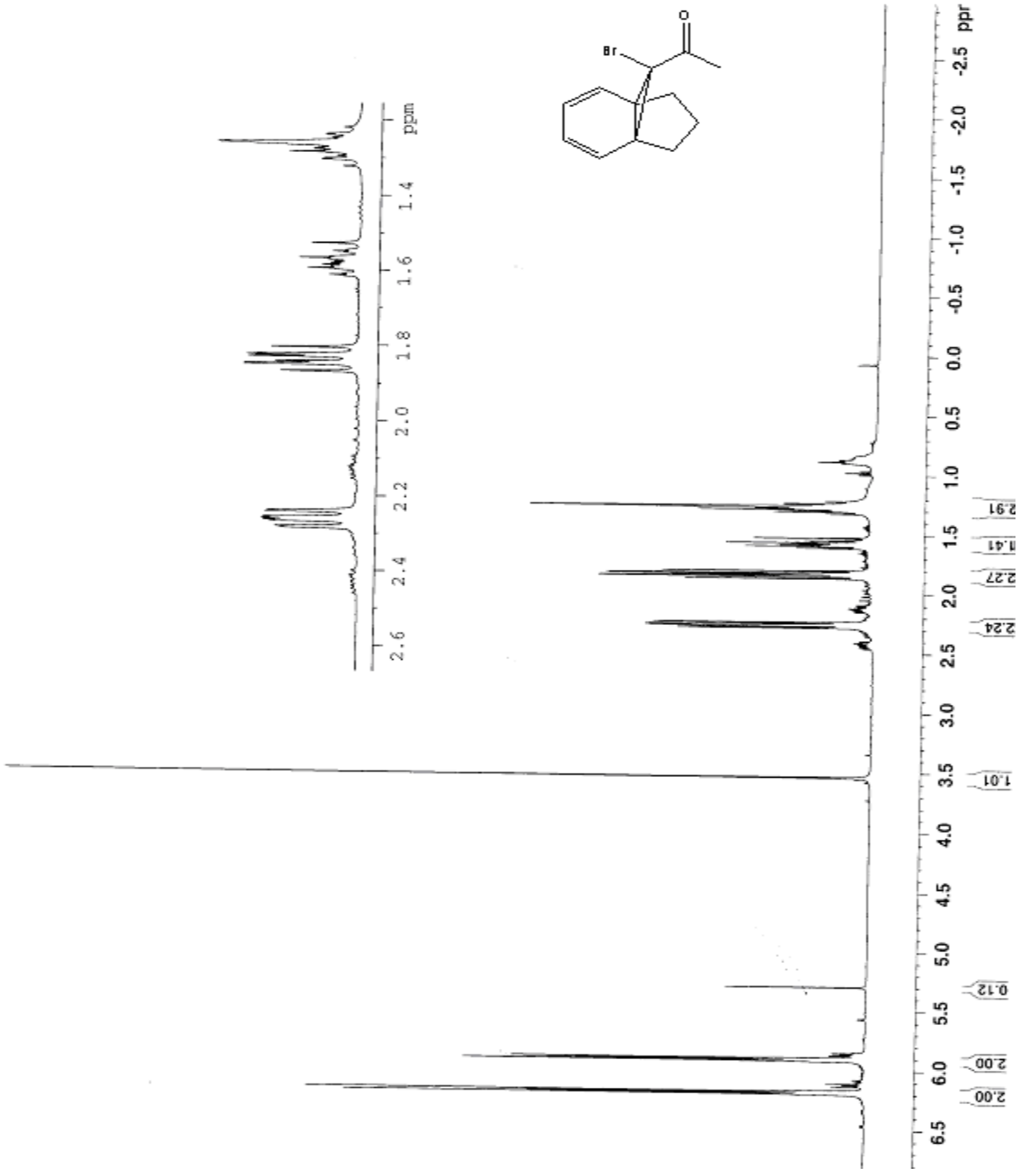


Figure A.16. ^{1}H NMR Spectrum of 10-endo-bromo-10-exo-carbomethyltricyclo[4,3,1,0]-deca-2,4-diene (**12**).

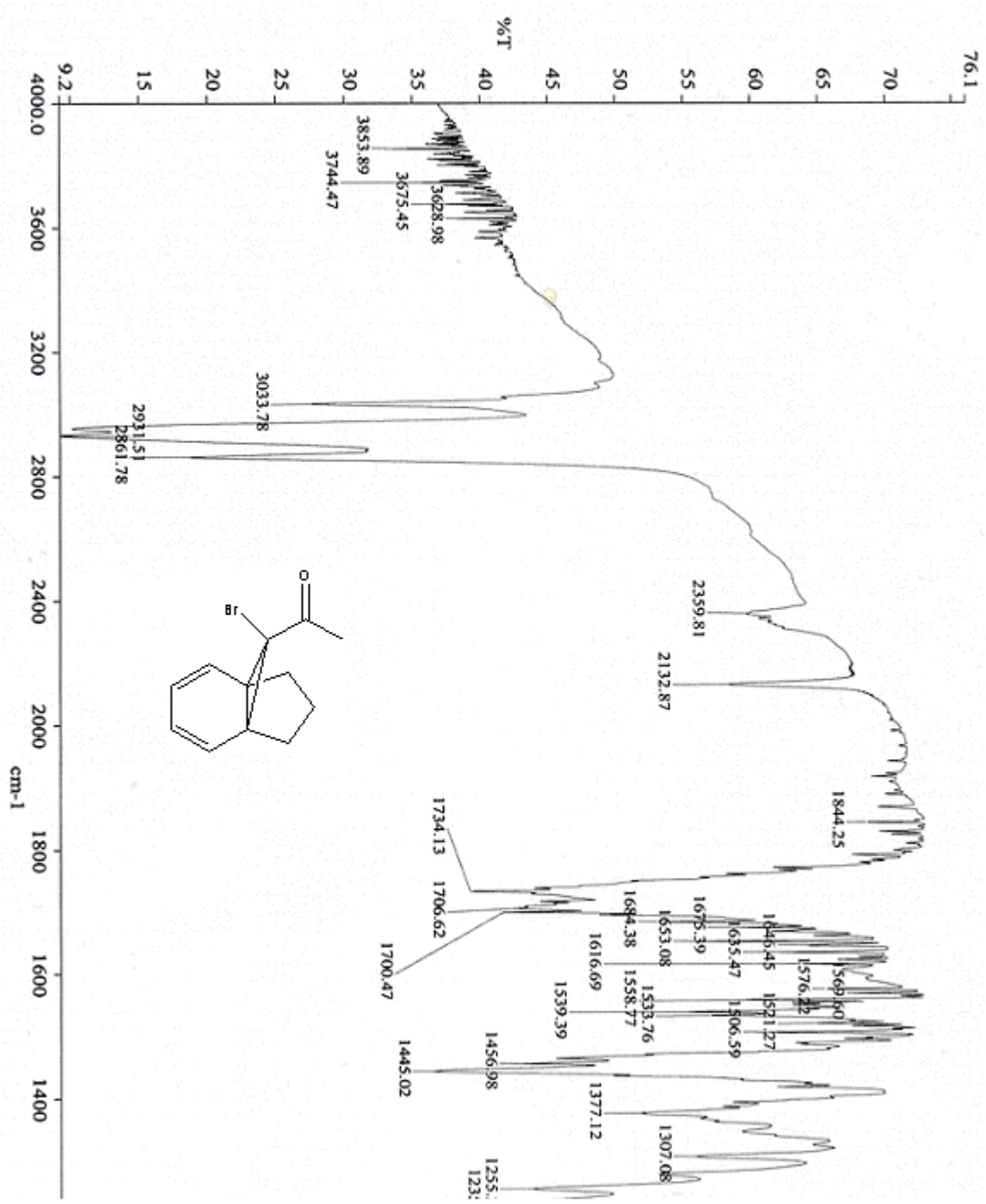


Figure A.17. IR Spectrum of 10-endo-bromo-10-exo-carbomethyltricyclo[4,3,1,0]-deca-2,4-diene (**12**).

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